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AFAL-TR-74-130
Volume I

MODULAR MULTI-SENSOR DISPLAY SYSTEM DESIGN STUDY

Volume I Requirements Analysis and Design Studies

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This technical report has been reviewed and is approved for publication.

Stephen H. Young
Information, Presentation, and Control Group
Information Management Branch

FOR THE COMMANDER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study of the requirements for and the design of a Modular Multi Sensor Display System was conducted. The purpose of the study was to perform the functional design of core and special module, that, when integrated together, perform the digital scan conversion, digital symbol generation, and display functions of multiple Air Force Avionics Systems. Specifically, the requirements were derived from the avionics sensor systems aboard F-4, A-7, F-106, F-111 and B-1 type aircraft. An analysis

Item 20. Abstract (continued)

was also performed to insure that the design was compatible with the spatial resolution, dynamic range and temporal response of the human operator.

The design study resulted in the definition of 20 core modules with universal system applicability and six special modules to perform specific interface and special mode functions. The resulting design was partitioned onto both LSI modules and discrete MSI printed circuit card modules. A programmable controller was designed to allow simple modification and growth for both the scan converter and symbol generator.

A tradeoff analysis was conducted to compare the modular design with existing analog techniques and with a discrete digital design to meet the specific display system requirements of the A-7 aircraft. Physical characteristics, cost of ownership, reliability, and maintainability were the key factors of this tradeoff. The modular design, although consisting of more circuitry to provide the multi-system flexibility, provides significantly improved reliability over the analog design and has a lower cost of ownership than the other alternatives. The lower cost is due to reduced development costs since "off the shelf" modules can be used, and to lower module costs due to the larger quantities produced. The recommendation from this study is the development of a MMSDS brassboard to demonstrate the modular concept and to evaluate the programmable controller functions as applied to various avionics systems.

FOREWORD

This report, submitted May 1974, covers the work accomplished during the period of May 21, 1973 through February 21, 1974 under Contract F33615-63-C-1267, 20030606, Modular Multi-Sensor Display System Design Study. The work was supported by the United States Air Force Avionics Laboratory (AFAL), Wright Patterson Air Force Base, Dayton, Ohio. The Technical Monitor was Mr. S. H. Young of AFAL/AAM. The report is divided into three volumes: Vol. I Requirements Analysis and Design Studies, Vol. II Detail Design and Applications Analysis, and Vol. III Tabulation of Sensor - Display Parameters. (Confidential)

The work was accomplished by the Display Systems and Human Factors Department of Hughes Aircraft Company under the direction of Mr. J. L. Heard as Program Manager and Mr. E. W. Opittek as Project Engineer. Special acknowledgement is given to the following individuals for their contributions to this report.

Mr. W. C. Hoffman acted as technical consultant and performed a major editing function. Messrs. W. L. Carel, R. J. Vanderkolk and Mr. M. Hershberger were responsible for defining the operator requirements. Mr. G. Wolfson was responsible for the contrast enhancement analysis and symbol generator tradeoffs. Mr. B. W. Keller was responsible for the detail module design with assistance from Messrs. M. D. Pruznick, S. E. Whiteside, J. R. Phelps, and R. M. Smithers. Mr. E. J. Dragavon performed the sensor criteria analysis and the actual research and tabulation of the sensor parameters was achieved by Mr. J. Stoltz. Mr. J. L. Bellock performed the cost of ownership and reliability analysis. Ms Anita Stoudt assisted in the report preparation.

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1.0 INTRODUCTION AND SUMMARY

1.1 Background

The display of data from a variety of sensors having different data rates and formats on a common indicator has always been attractive and has resulted in the development over the past several years of a progression of multi-mode display systems ranging from dual-persistence cathode-ray-tubes to direct view storage tubes, analog scan converter tubes and digital scan conversion techniques. Numerous studies and applications have shown that a scan conversion function along with a high performance television compatible CRT display provides the best potential performance and flexibility. However, experience with analog scan conversion in field applications has demonstrated an inherent low reliability, poor performance and high cost of ownership.

Developments in digital technology, particularly in solid state memories and in MSI/LSI packaging density has made the implementation of a totally digital scan converter a reality. This all digital mechanization provides an inherent improvement in reliability, maintainability, and flexibility with a significantly reduced cost of ownership. Several specific designs of digital scan converter/display systems for particular aircraft systems have already been proposed. The purpose of this study was to expand the specific design concepts to a modular scan converter/display system which would be compatible with multiple aircraft configurations including both current systems and future applications.

Such a modular design would be comprised of certain core modules which would be combined together to meet the requirements of various existing and new aircraft. Also, special modules unique to a specific system or mode would be designed as required. The advantages of such an approach include: lower cost of ownership due to minimized new system development and lower maintenance, spares, and training costs; increased reliability over existing analog systems; adaptability to new digital display and processing techniques.

1.2 Study Program

The modular multi-sensor display system (MMSDS) study program consisted of six major tasks:

1. A sensor display requirements analysis based on a survey and tabulation of the parameters of several existing or projected Air Force avionics sensor systems.

2. An evaluation of the human operator characteristics and their effect on the display design requirements.

3. The development of design criteria for determining the performance of a display system with respect to the sensor and operator characteristics.

4. The evaluation of alternate design mechanizations to determine an optimum design approach.

5. The functional design, partitioning and detail design of the MMSDS core and special modules.

6. An analysis of the application of the MMSDS to a specific avionics system to determine the cost and advantages of the MMSDS design.

The structure of this report follows the task organization.

Volume I is dedicated to requirements analysis and design studies.

Section 2.0 (Volume I), Functional Requirements, documents the results of task 1 and 2 and provides a complete summary of the sensor parameters for 25 radar and electro-optical systems and the human operator characteristics in terms of spatial resolution, dynamic range and temporal response. These parameters form the basis of the MMSDS design requirements and are tabulated in Table 1.

TABLE 1. SUMMARY OF DISPLAY SYSTEM FUNCTIONAL REQUIREMENTS

Display Formats

Radar

Air-to-air B-scan

Ground map sector PPI

Expanded sector PPI

Squinted side looking strip map

High resolution ground map patch

Air-to-ground ranging

Terrain following E-Square scan

Electro-Optical

Down looking line scan strip map

Air-to-air IR C-scan

Forward looking infra-red (FLIR) raster

Television raster

(Continued next page)

(Table 1, continued)

Sensor Parameters

Radar	
Range	1.0 - 200 n.mi.
PRF	300 - 5000 hz
Az/El Beamwidth	0.5 to 10°
Az Scan Limits	±90°
El Scan Limits	±60°
Scan Rates (Az & El)	50 to 250 deg/sec
Pulse Width	0.1 to 2.5 μsec
Video BW	0.5 to 10 Mhz
Dynamic Range	20 - 40 db
Electro-Optical (EO)	
TV Bandwidth	5 - 25 Mhz
Dynamic Range	40 - 100 db
EO Line Scan Rate	500 - 2000 Hz
Scan Angle	±60°
EO Line Scan BW	Up to 1 Mhz
Number of Line Scan Detectors	1 to 10

Operator Requirements

Radar display	
Active Raster Lines	≅100 per inch
Pixels per Inch	>50, <100
Dynamic Range	>10:1, <1000:1
Gray Scale Quantization	≧2 bits (4 shades)
Average Effective Luminance, fL	>0.05 x adaptation luminance (day), ≧0.1 fL (night)
Phosphor Color	Green
Frame Rate	30 Hz

(Continued next page)

(Table 1, concluded)

Operator Requirements (Continued)

Electro-Optical display

Characteristics	Analog Display	Quantized Display
Active Raster Lines	≅100 per inch	≅100 per inch
Pixels per Inch	N. A.	>50, <100
Dynamic Range	>100:1, <1000:1	>100:1, <1000:1
Gray Scale Quantization	N. A.	≥4 bits (16 shades)
Average Effective Luminance, fL	>0.05 x adaptation luminance (day), ≥0.1 fL (night)	>0.05 x adaptation luminance (day), ≥0.1 fL (night)
Phosphor Color	Green	Green
Frame Rate	30 Hz	30 Hz

Section 3.0 (Volume I), Design Performance Criteria, relates the performance requirements to the mechanization parameters and provides the design tools necessary to evaluate alternate mechanizations and optimize the design approach. Specific mechanization parameters such as A/D converter sampling frequency, memory size and display size are determined from the sensor parameters such as pulse width, range scale and display format.

Section 4.0 (Volume I), Mechanization Tradeoffs, contains the major design trade studies which were performed to determine the optimum design approach. Tradeoffs were made in five major areas: 1) selection of display sweep formats, 2) determination of basic scan converter architecture, 3) selection of memory tape, size and structure, 4) determination of digital scan converter controller architecture, 5) determination of optimum symbol generator configuration. A summary of the major conclusions arrived at as a result of the tradeoff studies is given in Table 2.

Volume II of the report is dedicated to the detail module design and application tradeoff analyses. The detail design and partitioning of the core and special modules based on meeting the requirements are presented in Section 2.0 of Volume II.

Section 3.0 (Volume II), Applications Analysis, shows how the "core" and "special" modules are configured for various avionics systems. A comparison of three display systems configured for the A-7 aircraft is presented which evaluate an analog scan converter/display, a digital scan converter/display and the modular-multisensor display system (MMSDS). Physical parameters, cost, reliability, and maintainability were the major parameters compared. A cost of ownership analysis, reliability analysis and physical system description are also included in this section.

Volume III is a classified volume (Confidential), listing the pertinent sensor parameters used to derive the MMSDS mechanization parameters.

TABLE 2. CONCLUSIONS FROM DESIGN TRADEOFF STUDIES

- Display all video and symbology in a horizontal television format.
- Utilize a data bus control architecture with separate memory, integrator, and controller.
- Use MOS random access solid state memory.
- Use microprocessor type controller, programmable to provide mode and system modifications.
- Generate symbols in-raster using programmable chain type symbol generator.

1.3 Recommended Design

The results of the system design and application analysis indicates that the modular multi-sensor display concept does provide a lower cost of ownership system. The recommended design is shown in Figure 1. It consists of a digital scan converter and digital symbol generator both of which operate under control of identical microprocessor controllers. Changing of modes, parameters and growth are achieved by reprogramming the memory portion of the controllers without any hardware changes. Increased resolution is obtained by expanding the modular display refresh memory. Input radar video in any format is digitized, processed and buffer stored in the integrator and stored in the digital memory. Besides the radar conversion, line scan EO video can also be scan converted and a frame of TV or FLIR video can be frozen for more detailed viewing. Readout of the memory is achieved in a standard television raster format providing composite video interface and easy recording on video tape. The modular display indicator unit is capable of displaying video in a horizontal television type raster of from 525 to 1023 lines. The display CRT module is selected based on the resolution required and the physical limitation of the cockpit installation. A programmable chain type symbol generator permits the presentation of any symbol shape and symbol repertoire mixed in the TV raster. Input control signals are accepted from either the standard Air Force Digital Avionics Interface System (DAIS) bus MUX interfaces or through special interface modules designed to convert existing system interfaces to a digital parallel format. DAIS is the Air Force advanced concept to provide a mission flexible total information management system consisting of modular subsystems. A summary description of the "core" and "special" modules is provided in the following paragraphs.

1.3.1 Digital Signal Transfer Unit Core Modules

1. Video Receivers and A/D - Buffers and translates input video and syncs to digital TTL logic levels.

2. Integrator and Truncator Memory - Memory module used with input radar video processing functions.

3. Integrator, Peak Detector and Truncation Logic - Processes input radar video to optimize characteristics of digitally sampled video.

4. Controller - Programmable microprocessor type controller to generate all mode, built-in-test, and control signals to both the scan converter and symbol generator functions. Two identical controllers can perform this function. The input control interface to the DAIS is also provided in this module.

5. Controller Memory - Storage for all system control programs. Mode and system parameter modifications can be made by reprogramming this module.

6. Display Refresh Memory - Modular memory for storage of digitized radar or EO video and symbology. Basic module stores 256 x 256 elements and contains all necessary input and output logic.

7. Memory Input Address Generator - High speed logic module commanded by system controller to generate memory load address sequences as a function of format.

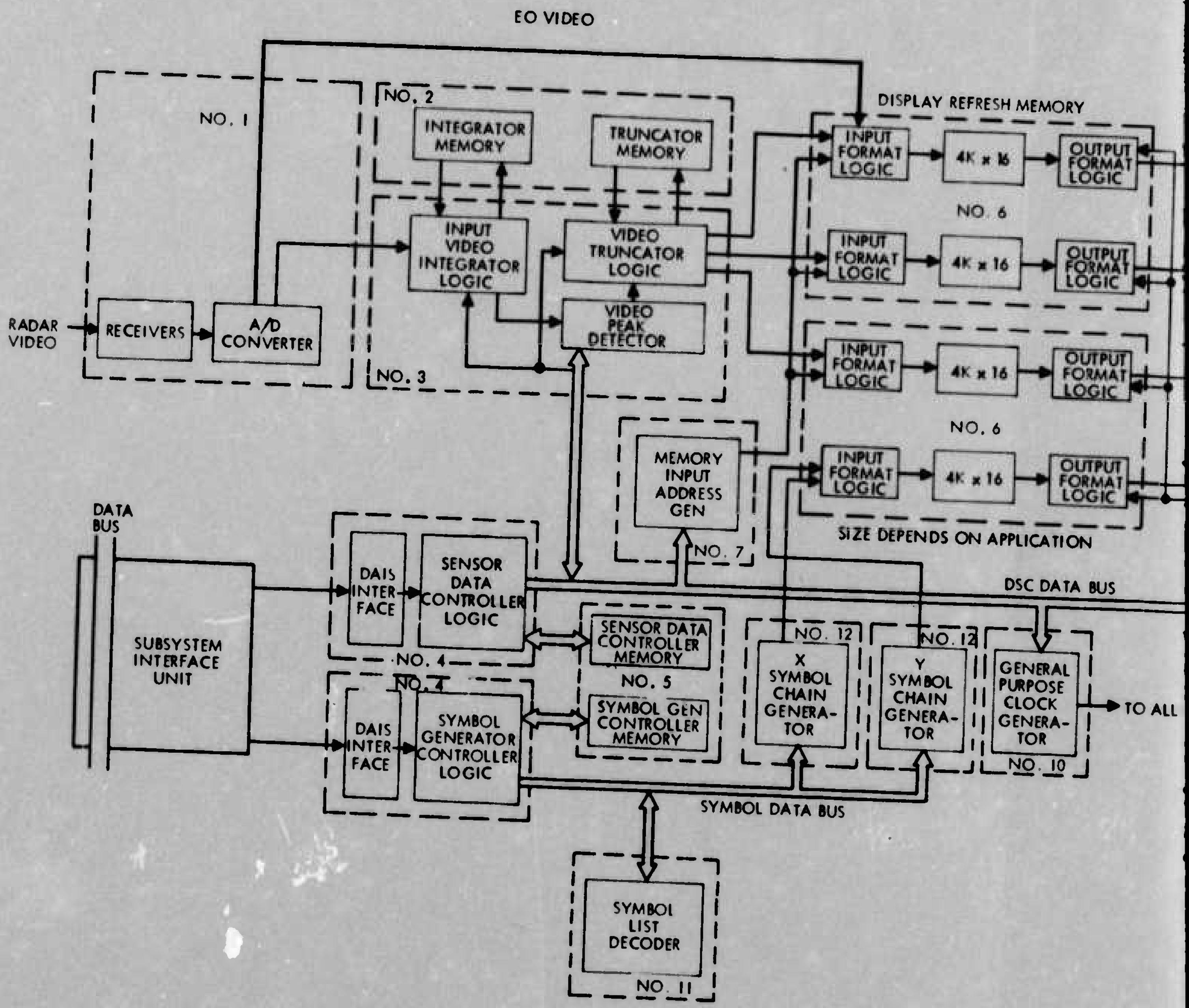
8. Memory Output Address and Display Sync Generator - Generates read address to display refresh memory to provide television raster compatible video. Also generates standard EIA composite syncs.

9. Output Video Processing - Performs output video D/A conversion, sync and symbol mixing, filtering and gamma shaping to optimally match the display CRT transfer function.

10. Clock Generator - Generates all necessary system clock rates and phases under command of the system controller.

11. Symbol List Decoder - Transforms symbol control signals to command signals to the symbol chain generators.

12. Symbol Chain Generator - Two identical X and Y modules generate X and Y addresses to the symbol refresh portion of the Display Refresh memory.


EO VIDEO
DISPLAY REFRESH MEMORY
NO. 1
NO. 2
INTEGRATOR MEMORY
TRUNCATOR MEMORY
INPUT FORMAT LOGIC
4K x 16
OUTPUT FORMAT LOGIC
NO. 6
INPUT VIDEO INTEGRATOR LOGIC
VIDEO TRUNCATOR LOGIC
RADAR VIDEO
RECEIVERS
A/D CONVERTER
VIDEO PEAK DETECTOR
NO. 3
MEMORY INPUT ADDRESS GEN
NO. 7
SIZE DEPENDS ON APPLICATION
DATA BUS
SUBSYSTEM INTERFACE UNIT
DAIS INTER-FACE
SENSOR DATA CONTROLLER LOGIC
NO. 4
SENSOR DATA CONTROLLER MEMORY
NO. 5
SYMBOL GEN CONTROLLER MEMORY
SYMBOL GENERATOR CONTROLLER LOGIC
DSC DATA BUS
NO. 12
X SYMBOL CHAIN GENERA-TOR
Y SYMBOL CHAIN GENERA-TOR
GENERAL PURPOSE CLOCK GENERA-TOR
NO. 10
TO ALL
SYMBOL DATA BUS
SYMBOL LIST DECODER
NO. 11

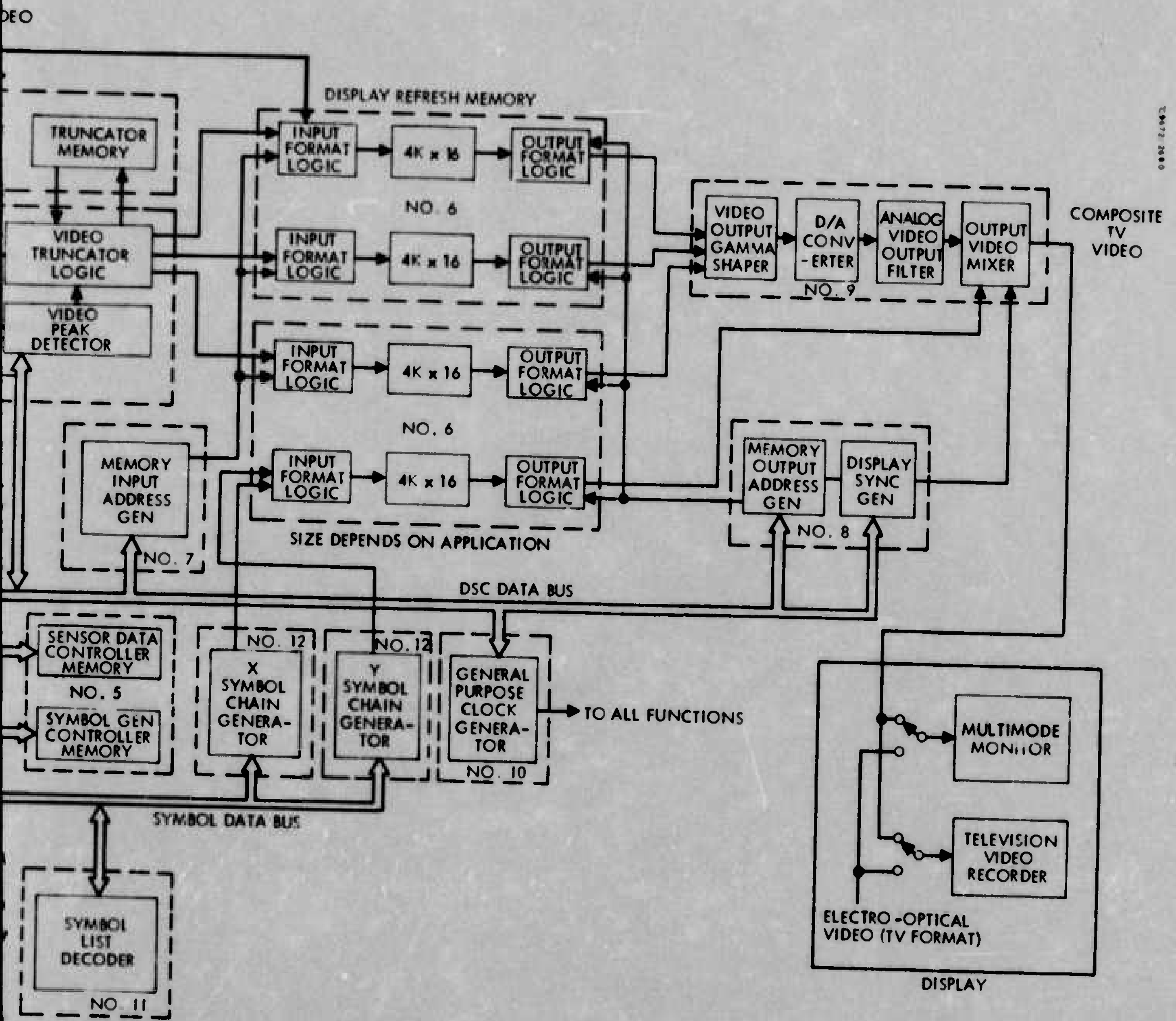


Figure 1. Partitioned Modular Display System

1.3.2 Digital Signal Transfer Unit Special Modules

1. Non DAIS Interface Module - Converts analog signals, synchro signals, etc., to the digital parallel format required by the MMSDS system controllers.

2. Special Purpose Clock Generator - Generates variable clock rates to perform such special functions as ground range sweep correction and terrain following E^2 displays.

3. Video Processing Module - A histogram equalization module is described which enhances the radar video display. Other video processing modules may also be designed.

4. Out of Scan Blanking Module - Generates display blanking signal for area outside the limits of the PPI radar scan pattern.

5. Video Aging Module - Allows generation of variable persistence type of display presentation on multiple frame processed air-to-air search display.

1.3.3 Multi Mode Display Core Modules

1. Video Amplifier/Blanking Module - Receives selected composite video, strips off syncs and drives the CRT control grid.

2. Horizontal AFC/Deflection Module - Generates horizontal sweep signals from input syncs to provide 525 to 1023 line television raster.

3. Vertical Deflection/Sweep Fail Module - Generates the 60-Hz vertical deflection signal from input syncs. Also senses sweep failure and blanks display to prevent CRT damage.

4. Dynamic Focus/Horizontal Linearity Correction Module - Provides dynamic CRT spot focus signal as a function of the beam deflection position. Also provides correction function to insure linear deflection over the entire display.

5. High Voltage Power Supply - Generates all CRT and video amplifier voltage forms. Anode voltage adjustable from 15 KV to 20 KV depending on CRT.

6. Low Voltage Regulator - Regulates voltage from power transformer and rectifiers which are discrete components mounted on chassis. This module can also be used in Digital Signal Transfer Unit.

7. BIT Generator/Data MUX - Generates internal test pattern for display in CRT. Module outputs are checked, failure detections are made available on DAIS interface bus.

1.3.4 Multi-Mode Display Unit Special Module

CRT - Potted CRT assembly with magnetic deflection yokes. Size depends on application.

1.4 System Applications

The MMSDS design was applied to several avionics systems to determine the number of "core" and "special" modules required in each system. The results of this analysis is tabluated in Table 3. Each system uses all eleven types of core modules and various number of memory modules depending on the resolution requirements. The F-111 systems require two complete digital scan converter channels and therefore require approximately twice as many logic and memory modules as single channel systems. The "special" modules are primarily interface modules to convert the input data formats to compatible digital data word formats.

TABLE 3. MODULAR APPLICABILITY SUMMARY TABLE

Aircraft	Digital Signal Transfer Unit				Multi Mode Display		
	Core Modules	Memory Modules	Special Modules	DSTU Total	Core Modules	Special Modules (CRT Only)	Total Modules
F-4 (C, D & E)	13	4	4	21	16	2	18
F-106	13	2	3	18	8	1	9
A-7	13	4	5	22	8	1	9
F-111 (A, D, FB-111 & B-1)	26	9	8	43	16	2	18
B-1 EAR	26	26	3	55	16	2	18
F-15	13	2	2	17	8	1	9

A study was made of the application of the MMSDS to the A-7 avionics sensor system with a DAIS type interface. Four alternate display systems including an analog scan converter system, discrete digital system and both an LSI and MSI modular system were compared. The analog system include both an analog scan converter and symbol generator. The discrete digital design was an optimal digital design to meet the requirements of the specific A-7 application. The LSI system was the modular design partitioned on large 2.2 inch diameter bipolar IC wafer and hybrid circuitry modules. The MSI design was the same design mechanized with MSI and SSI integrated circuits mounted on printed circuit card modules. A detailed cost of ownership analysis of the alternates was conducted whereby the cost components were identified. A reliability analysis was also conducted. Both the LSI and MSI modular signal transfer units and display indicators are physically described. The results of this trade-off study are summarized in Table 4.

TABLE 4. SUMMARY TRADEOFF TABLE ALTERNATE A-7/DIAS DISPLAY SYSTEMS

	Analog System	Discrete Digital System	Modular MSI	Modular LSI
Number of Modules	N. A.	29	34	28
Weight, lbs	65	45	47	40
Volume, cu ft	1.25	0.7	0.7	0.7
Power, watts	290	350	403	403
MTBF, hrs	190	765	670	1890
MTTR, hrs	4	1	0.5	0.5
Maintenance Adjustments	41	6	6	6
Relative Cost of Ownership (1st System)	1.7	1.0	1.1	1.0
Delta Cost (2nd System)	1.7	1.0	0.8	0.7
Delta Cost (3rd System)	1.7	1.0	0.7	0.6

1.5 Conclusions and Recommendations

The cost analysis of the modular system indicates a total program savings which increases with each successive system procurement using the modular design concept. These program savings can be further increased with improvements in maintenance and spares provisions that take advantage of the use of standard modules in different avionics systems. A key feature that contributes to the cost savings is LSI implementation of the "core" modules. The higher reliability and lower production cost of LSI leads to a significant program savings in multiple system buys where the LSI development cost can be amortized over several systems. A second key feature of the modular system concept is the use of a programmable microprocessor to control the scan converter and symbol generator functions. This enables adaptation of the modular display system to different avionics system by simply reprogramming the microprocessor controller.

A two step development of the modular multi-sensor display system (MMSDS) is recommended. The first step would be the design and fabrication of an exploratory development model (EDM) utilizing discrete SSI and MSI digital logic elements but partitioned into LSI compatible functional modules. This EDM would serve as a vehicle to test and demonstrate the modular concept and to evaluate programming functions for the microprocessor controller. Alternate memory sizes could be mechanized to demonstrate various resolution systems and the microprocessor could be reprogrammed to demonstrate and evaluate the flexibility of the design. It would also provide the basis for the second stage of development; the design and fabrication of LSI and hybrid modules. This LSI development could be oriented towards fabrication of the "core" modules or towards fabrication of a production system for a specific aircraft application.

2.0 FUNCTIONAL REQUIREMENTS

2.1 Introduction

In this section the functional requirements of the Modular Multi-Sensor Display System (MMSDS) are presented. These requirements are summarized in Table 5. The results of a sensor analysis are reported in the form of a tabulation of the display parameters of 25 Air Force radar and electro-optical sensor systems. The range in the value of these parameters, extended for growth, represents the design requirements of the MMSDS. In addition to the sensor video scan conversion requirements, symbol generation, electrical interface, and physical requirements are presented. The results of an operator requirements analysis are also presented in this section. This analysis was conducted in order to insure compatibility with the spatial resolution, dynamic range and temporal response of the human operator. It was based to a large extent on recent Hughes laboratory study data on sampled video displays.

2.2 Sensor and Physical Requirements

2.2.1 Airborne Radar Sensor Analysis

The functional capabilities, modes, and associated signal/data processing equipment of airborne radars vary widely because of differences in missions, aircraft size, and the state of technology at the time the system was procured. Radar systems, therefore, vary from the simple, single-mode system for limited role aircraft, to the highly sophisticated, multi-mode configurations for advanced manned airborne weapon systems.

Functional Description of Radar Modes

A description of the characteristics and use of airborne radars in their various modes is provided in the following paragraphs.

Forward Sector Ground Map (FSGM)

The radar antenna scans through an azimuth sector in the forward direction while transmitting and receiving radar pulses at relatively low pulse repetition frequencies (prf) which are selected to provide unambiguous range information at the selected range scale. The resulting video is an amplitude modulated analog signal train representing reflected energy level as a function of range (which is proportional to the elapsed time between pulse transmission and echo reception). The ground map is generated by storage (in real time) and displaying of successive range sweeps in proper relationship to one another in range versus azimuth coordinates; normally a plan-position indicator (PPI) format is used to provide an undistorted ground map; however, orthogonal range versus azimuth (B-scan) formats have been used and are acceptable for FSGM operation in certain operations. The antenna typically scans bi-directionally (left to right and right to left) at scan rates that vary depending on the specific radar implementation and selected range scale. Azimuth coverage is selectable and in some applications positionable within the antenna gimbal limits. Typically the scan pattern is roll stabilized covering a single elevation bar; however, multi-bar scans with options of up to 8 bars are sometimes available. The antenna beam is normally shaped in elevation to provide optimum "illumination" of the terrain over the selected range interval. Optional pencil beam operation in elevation may be available with a beam width in the 1° to 5° range. Since ground "illumination" is limited to the beam width, this type of operation requires antenna tilt control to assure adequate ground return in the range interval of interest; it is also appropriate for use at low altitudes where the entire range interval of interest is within the pencil beam due to low grazing angles (however, poor image definition due to shadowing at low grazing angles is a potential problem).

The range sweep interval is determined by the prf, and the active sweep time is limited by the selected range scale (real-time two-way transmission time at the speed of light; i. e., 12.38 microseconds per mile). The range resolution is determined by the radar pulse width. To provide an acceptable signal-to-noise level, relatively long pulses must be used for long ranges, white short pulses are used for short ranges; very short pulses are used for some applications. Pulse compression techniques are sometimes used to maintain a short effective radar output pulse width (resolution) while providing the power advantages of long transmittal/received pulses.

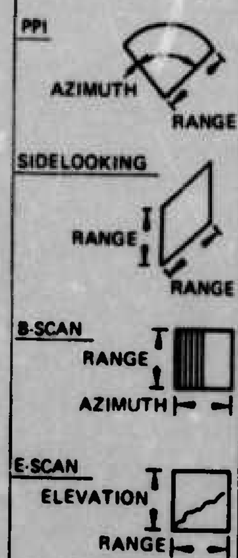
The azimuth resolution in the FSGM mode is determined by the beam width. Consequently, there are relatively few azimuth resolution cells within one azimuth scan. For example, a radar with a 2° azimuth beam width scanning through ±45° provides an effective azimuth resolution of only about 45 cells per scan; the number of range sweeps per azimuth scan for the same radar assuming a prf of 1000 per second and a scan rate of 100°/sec is 900 which represents 20 azimuth "samples" per resolution cell. Conventionally all range sweeps are displayed resulting in spatial and signal level integration (due to overlap of adjacent display lines) to enhance overall image quality. Equivalent video integration capability must be provided in the modular multi-function display.

The video bandwidth for FSGM is in the 5 megahertz category. The dynamic range varies from 16 to 30 dB (or higher) depending on the specific configuration. Linear, logarithmic or lin/log video amplification may be used. Automatic gain control is generally provided – gain compensation as a function of range may be included. Operator control of the radar (IF) gain as a function of specific observed conditions is generally available.

The time-of-return-based radar range is slant range to the ground. Ground range correction, if required, must be provided in the display by controlled variation of the sweep rate or sampling intervals according to a known deterministic relationship which includes aircraft altitude as a parameter.

RADAR

Modes	Formats	Range of Parameters		Operator for C
Ground Map and Air-to-Ground		Range	0.2 to 200 n. mi.	Active Raster L
Sector PPI		PRF	300 - 5000 hz	Pixels per inch:
Expanded PPI		Az/El Beamwidth	0.5 to 10°	Dynamic Range:
Sidelooking Strip Mapping		Az Scan Limits	±90°	Gray Scale Quan
High Resolution Ground Map Patch		El Scan Limits	±60°	Average effectiv luminance, fL*
Doppler Beam Sharpened PPI		Scan Rates (Az & El)	50 to 250 deg/sec	Phosphor Color:
Air-Ground Ranging		Pulse Width	0.1 to 2.5 μsec	Frame Rate:
Air-to-Air		Video BW	0.5 to 10 MHz	
B-Scan		Dynamic Range	20 - 40 db	
B-Scan (Range Rate)				
Acquisition				
Track				
Low Level Flight				
Terrain Avoidance				
Terrain Following				



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ELECTRO-OPTICA

Modes	Formats	Range of Parameters		Opera
Infrared Search and Track (IRST)		TV Bandwidth	5 - 25 MHz	Active Raster Lines:
EO Line Scan (Laser or IR)		Dynamic Range	40 - 100 db	Pixels per inch:
Forward Looking TV (TISEO, LLTV, TV Weapons)		EO Line Scan	500 - 2000 Hz	Dynamic Range:
Forward Looking IR (FLIR)		Scan Angle	±60°	Gray Scale Quantization:
		BW	Up to 1 MHz	Average Effective luminance, fL:
		No. of Detectors	1 to 10	Phosphor Color:
				Frame Rate:

TABLE 5. REQUIREMENTS SUMMARY

RADAR

...meters
2 to 200 n. mi.
0 - 5000 hz
5 to 10°
0°
0°
to 250 deg/sec
1 to 2.5 μsec
5 to 10 MHz
- 40 db

Operator Derived Characteristics for Quantized Display	
Active Raster Lines:	≅100 per inch
Pixels per inch:	>50, <100
Dynamic Range:	>10:1, <1000:1
Gray Scale Quantization:	≥2 Bits (4 shades)
Average effective luminance, fL*	>0.05 x adaptation luminance (day), ≥0.1 fL (night)
Phosphor Color:	Green
Frame Rate:	30 Hz

*The luminance the operator sees

Other	
Symbology	
Repertoire	Variable - Mil Std 884 for reference
Format	Variable line TV raster
Display Parameters	
Line Standard	525 to 1023 per EIA standards RS 170 and RS 343
Aspect Ratio	1:1 and 4:3
Resolution	100 television raster lines/inch
Luminance	Sufficient to provide five shades of gray ($\sqrt{2}$) in 10K fL ambient.
Interface	
Input Signal	
DAIS Interface:	Digital Parameter Control with analog video
Non-DAIS Interface:	Synchro, analog, and digital signals as they exist in system.
Output Signals to Display:	Composite video per EIA STD RS 170 or 343
Physical:	Must fit within O&M system

ELECTRO-OPTICAL

...eters
25 MHz
- 100 db
0 - 2000 Hz
0°
to 1 MHz
o 10

Operator Derived Characteristics	Analog Display	Quantized Display
Active Raster Lines:	≅100 per inch	≅100 per inch
Pixels per inch:	N.A.	>50, <100
Dynamic Range:	>100:1, <1000:1	>100:1, <1000:1
Gray Scale Quantization:	N.A.	≥4 Bits (16 shades)
Average Effective luminance, fL:	>0.05 x adaptation luminance (day), ≥0.1 fL (night)	>0.05 x adaptation luminance (day), ≥0.1 fL (night)
Phosphor Color:	Green	Green
Frame Rate:	30 Hz	30 Hz

Other
Same as Radar

Auxiliary signals typically provided by the radar to the display include: azimuth and elevation position of the antenna (angles, sine/cosine, direction cosines), sweep triggers, video gates, antenna scan direction and turn-around signals as well as test data. The gates, triggers and video are typically transmitted directly to the display — the remaining signals may be routed through other elements of the weapon systems, i. e., a central data processor. Additional data — e.g., symbol information representing prestored target/aim point/fix point position, scale markings, cursors, etc. — may be provided by external weapon system elements for use in conjunction with the FSGM display presentation.

A special display feature implemented in certain FSGM radar systems is the sector expand mode wherein a portion of the available data is displayed and expanded around a designated terrain feature whose image remains stationary on the display on successive scans. This mode provides an improved scale factor and stationary target image to aid the observer in identification and precision designation. Functionally similar display capabilities, e. g., freeze and expand, should be provided in the modular multi-sensor display for these radar systems.

Air-to-Ground Ranging (AGR)

There exists a variety of air-to-ground weapon delivery techniques which use different sets of inputs and equations in the determination of steering guidance and release solutions. The air-to-ground weapon delivery accuracy can be improved significantly if accurate target range measurements can be made just prior to or during attack runs. Air-to-ground radar ranging modes have been devised to provide range measurements to targets designated by the aircrew using symbology on Head-Up Displays, Optical Gun Sights, and Helmet Mounted Sights. Typically the radar operates at low prf with the antenna boresighted or driven by external command signals (e. g., computer, hand control, tracking sensor). Radar range along the line of sight is measured (continuously or at discrete commands) and transmitted to the computer for use in the steering guidance and weapon delivery computations. Special signal processing may be used to determine boresight ranges in view of the relatively large beam widths that are available and relatively high side-lobe levels and altitude returns. The antenna is essentially stationary during air-to-ground ranging. The video display requirement is limited to presentation of the received video as a function of range at the (essentially fixed) antenna azimuth position. The video and auxiliary signals are signals are similar to the corresponding FSGM signals.

Terrain Avoidance (TA)

Terrain avoidance radars provide terrain elevation information in addition to the conventional range and azimuth data of FSGM operation. It is generally used in low altitude flight to determine optimal horizontal maneuvers such that exposure to detection, tracking and countermeasures is minimized.

Several basic TA techniques have been devised, including (a) level slicing of FSGM video such that only terrain protruding above the selected clearance plane is displayed and video received from points below this plane are blanked, (b) mixing of safe clearance symbol and bore-sight range tracking pulses (at a pre-set depression angle) with FSGM video, and (c) off-boresight processing within the radar beam to determine terrain elevation as a function of range intervals and azimuth — a shades-of-gray presentation of azimuth versus elevation with discrete range intervals coded in different shades of gray is typical of this approach. The first two approaches have operating characteristics similar to the shorter range FSGM modes. Display operation is similar to the FSGM with the exception of added blanking signals and/or symbol inputs. The shades-of-gray TA technique requires storage and shades of gray encoding of range intervals as a function of azimuth and elevation. The necessary processing is accomplished on every radar sweep. The number of range intervals is limited to between five and ten. Conventional intensity modulated radar video is not provided.

Terrain Following (TF)

Terrain following radars (or modes) provide terrain elevation contour information in the forward direction to the aircrew and/or to the flight control system for steering guidance and/or automatic flight control in the vertical plane in order to maintain a low flight profile along a planned or selected flight vector. The radar operates in a low prf mode with the antenna nodding through a fixed angle in the vertical plane. The radar tracks the ground at the antenna boresight providing an output signal representing range as a function of elevation. The TF information is displayed as a range-to-ground versus elevation trace in orthogonal coordinates. The range dimension may be linear (E-scan) or exponential (E^2-scan). The TF video signal is binary and thresholded (with variable thresholds). In addition to the range-to-ground trace, a template representing the safe clearance plane in elevation versus range is displayed. This template is used as a reference for manual vertical maneuvers.

The TF information is supplied to data processing equipment which generates vertical steering guidance for display on the flight instruments (HUD, VSD). They may also be used directly for automatic flight control. In both cases the TF display is required for monitoring of system operation and rapid transition to manual control (when necessary).

Doppler Beam Sharpening (DBS)

Conventional FSGM systems are limited in azimuth resolution by the antenna beam width (1° to 4° typically). Doppler signal processing techniques have been developed whereby the effective beamwidth can be reduced by an order of magnitude or more. This type of processing requires intermediate storage and correlation of radar signals over a finite period of time.

Processing and storage constraints limit the rates and amount of data that can be processed. Synthetic video is provided to the display at rates which differ from the "raw" radar signal collection rates. Typical DBS parameters are: 1/4° effective beam width, ±45° azimuth coverage, 1- to 2-second frame time, 50- to 100-ft range resolution and 10-mile range coverage (which may be positionable out to 50 n. mi.). No beam sharpening is obtained at 0° azimuth since no doppler effect is present. DBS video is normally displayed as a sector PPI (or offset PPI).

Ground Moving Target Indicator (GMTI)

Processing techniques such as clutter referenced low prf signal processing (MTI) and coherent on receive doppler processing have been devised to distinguish between moving targets and stationary backgrounds. These methods require intermediate signal processing; hence the resulting information provided to the display is not in real time. The azimuth resolution is the same as for FSGM; however, range resolution is typically limited to 500 (or less) range bins. Velocity resolution as low as five knots can be achieved. Output video is binary: on when the velocity exceeds threshold and off elsewhere. Scan patterns and rates are similar to the FSGM. By appropriate timing of the MTI processor output signals, it is possible to mix the velocity returns with the basic FSGM format as a spatial background reference for moving targets.

Side Looking Strip Mapping (SLR)

Side looking radar systems have been developed primarily for reconnaissance; however, advanced weapon delivery concepts based on SLR are currently under intensive study and may be introduced operationally in the near future.

In SLR systems, the antenna is stabilized and positioned at a fixed angle to the side of the aircraft. The forward motion of the aircraft provides the scanning motion of the beam across the ground. The beam position is fixed in elevation and shaped to provide uniform ground illumination. Early SLR systems used "brute-force" techniques to maximize azimuth resolution — beam widths of 1 degree of less were achieved using large antennas. Prf's and data rates were similar to the FSGM; however, a display frame was built up in line-by-line (range sweep by range sweep) position requiring relatively long term display video storage or recording. Pulse compression resulting in 100 ft or better range resolution was employed. Delay line cancellation techniques were added for MTI processing.

Synthetic array processing, involving intermediate storage and correlation of "raw" radar video, provides very high resolution strip maps. The antenna may be squinted at various azimuth positions. Range "windows" varying from 1/2 to 20 n. mi. may be positioned along the sweep (cross track) from near 0 to 100 n. mi. Synthetic, intensity modulated video is provided to the display at rates which are limited by specific processing techniques which are used in their generation. The rates are typically slower than for "brute-force" radars. Pulse compression techniques are used to provide approximately matched range and azimuth resolution.

The forward motion of the aircraft provides the azimuth (scan) for SLR. Hence, the frame time is a function of aircraft speed and coverage. For example, a 10-mile square frame would require 1.7 minutes to build up at an aircraft speed of Mach 0.6. A "passing scene" presentation similar to a recorded strip map is desired for SLR to provide geometric continuity and natural orientation.

A further refinement of synthetic array SLRs is the tracking telescope (TTS) which provides discrete frames of synthetically processed radar video around a designated ground point. This is accomplished by repositioning of the antenna between frames and use of the aircraft motion to sweep it across the target for a sufficiently long interval to collect and process a full frame of high resolution imagery. Display interfaces are similar to the strip mapping modes with the exception of usually smaller frames, e.g., 1/4 to 2 miles (and corresponding frame intervals), and stepwise azimuth rotation of successive frames.

Appropriate symbols are added to SLR and TTS for target designation and position measurements. The required signals are provided by data processing equipment.

Air-to-Air Search and Track (A/ASTR)

There exists a wide variety of air-to-air fire control search and track radars. Conventional low prf search/track radars have display interface parameters similar to FSGM radars. They generally employ multi-bar elevation search patterns. Their presentations are usually B-scans with intensity modulation of the video; A-scan (amplitude versus range) and C-scan (elevation versus azimuth) formats have also been used. Pencil beams in the 2 to 5-degree beam regions are used. In general, the search scan limits and coverages are wider for A/A radars (or A/A modes) than for FSGM.

Air-to-air ranging modes are provided for short range air combat. The antenna may be nutated to provide broader coverage than the real beam width. Its line of sight may be boresighted or driven by computer inputs (to maintain target "illumination") or alternate tracking sensors.

Target acquisition and closed loop range and angle tracking are integral capabilities of most fire control radars. Logic and control capability are provided for manual positioning of the antenna (or small scan patterns) in azimuth and elevation and target designation with a range gate (1 to 5 μseconds) followed by activation of tracking circuits. When sufficient energy is detected within the gate, closed-loop tracking begins and is maintained until the target return is lost or return-to-search is initiated deliberately. The video presentation in the tracking mode is similar to air-to-ground ranging(AGR) with the exception that the display sweep tracks the target's position. The range gate and other auxiliary symbols may be mixed with the radar tracking presentation.

Advanced radar systems have been developed which operate at medium and high prf's providing air-to-air moving target capability in search and track and very high clutter rejection capability in look-down as well as look-up modes. Intermediate processing techniques are used providing thresholded hit/miss video. These signals are provided to the display at slower rates than the "raw" range sweeps.

In high prf radars the basic coordinates are range rate versus azimuth. Typically 500 doppler filters are used with an output rate of 1.5 milliseconds per range rate sweep and 8 millisecond period. The display format is range rate versus azimuth (B-scan). Special coding techniques (e.g., FM modulation) are used to provide data necessary for range determination. Thresholded radar signals may be provided to data processing equipment for automatic correlation, association and extrapolation in a track-while-scan mode (TWS). Radar data processor outputs are displayed symbolically as observations and/or track files in PPI tactical display formats.

Scan patterns and scan rates of doppler-processed air-to-air radars are similar to those of conventional radars; acquisition and tracking modes are also similar.

The Effect of Radar Characteristics on MMSD Design

The design of the MMSD must accommodate the full spectrum of airborne radars. The first step in the requirements analysis process, therefore, is to identify the radar systems of interest. Table 6 lists the aircraft and radar equipment considered in this analysis. A detailed tabulation of these radar parameters and a listing of the documents from which they are obtained, are provided in Volume III.

The intent of this analysis is to identify those sensor characteristics and parameters that have a direct and significant impact on multi-sensor display system design. Of particular interest are the radar performance parameters that effect the size or configuration of the digital scan converter memory, digital data rates, integrator characteristics and display resolution requirements. Table 7 is a list of significant radar parameters and an assessment of their probable impact on the design of the multi-sensor display system.

TABLE 6. RADAR EQUIPMENT LIST

USAF Aircraft	Radar Equipment
F-106, F-106A	MA-1, AN/ASQ-25
A-7D	AN/APQ-126
F-4C	AN/APQ-100
F-4D	AN/APQ-109
F-4E	AN/APQ-120
F-111A	AN/APQ 113, 110
F-111D	AN/APQ 130, 128
FB-111	AN/APQ 114, 134
F-15	AN/APG-63
B-1 (AMB)	AN/APQ-144, 146
B-1 EAR	Electronically Agile Radar (EAR)
F-5E	APQ-153

TABLE 7. RADAR PARAMETERS AFFECTING DISPLAY SYSTEM DESIGN

Parameter	Impact on Display System Design
Video Type; Analog or Digital	- Defines requirement for video A/D.
Range Scales	- Radar range establishes memory requirements.
Pulse Width (PW)	- Memory Size depends on resolution, range.
PRF	- PRF together with antenna azimuth beamwidth (BW) and antenna scan rate affects video integration requirements.
Antenna EL Beam Width (BW)	- Antenna EL BW and number of elevation bars determine number of elevation angle samples per elevation scan angle (TF modes)
Antenna AZ Beam Width (BW)	- Azimuth BW and azimuth scan angle determine number of azimuth resolution samples.
Antenna AZ Scan Rate	- Azimuth Scan rate together with PRF and azimuth BW determine azimuth angle sampling rate. - Also effects integrator design.
Antenna EL Scan Rate	- Limited impact for TF scans.
Antenna AZ Scan Angle	- Azimuth scan angle together with antenna azimuth BW determine the number of azimuth resolution samples required.

(Continued next page)

Table 7, concluded

Parameter	Impact on Display System Design
Antenna EL Scan Angle	- For TF, scan presentations determines memory requirements.
Video SNR	- Affects Integrator Design.
Video Dynamic Range	- Affects A/D converter requirements, memory size, quantization.
Formats	- Major impact on timing and control, memory addressing.
Number/Size Displays	- Affects cockpit installation.
Symbol Requirements	- Determines symbol generator technique and design.
Interface	- Defines receiver, registers, and buffer requirements.

2.2.2 Airborne Electro-Optical Sensor Analysis

Airborne electro-optical sensor systems vary widely in their capabilities, complexity, and technologies. Included in the airborne electro-optical sensors are the IR line scanner (IRLS), the IR Search/Track Set (IRST), Forward Looking IR (FLIR), and television (Low Light Level TV (LLLTV), Guided Weapon TV, and TISEO (Target Identification Sensor EO)). Electro-optical systems operate in the visual or IR regions of the electromagnetic spectrum and are passive systems.

IR system development is characterized as a high technology area that is undergoing rapid technological advances--especially in the development of high bandwidth detection devices, fast FOV scanning, and modularization. Despite continuing technological advances, several generic types of EO systems have evolved and have become well established by virtue of high volume operational use. A description of the broad classifications and use of these sensors is provided in the following paragraphs.

Forward Looking IR (FLIR)

Typical FLIR sensors use multi-cell detector arrays which are optically scanned at very high rates across the field of view such that the instantaneous signal level of each cell is indicative of the received energy within its spectral region from the corresponding azimuth and elevation position in object space (the scene seen through the IR window). The signal level of each cell is preamplified and further processed to provide a direct display or more typically, converted to a TV format for use on a standard TV monitor. The detector arrays are normally arranged vertically and scanned horizontally. They are shifted vertically by one-half cell space on alternate horizontal scans to provide an interlace pattern. Sensor arrays containing several hundred cells have been developed; however, since the number of cells is a major determinant of FLIR sensor cost, the number of cells used in operational equipment is limited, as a practical matter, to that which provides minimum acceptable image quality.

A wide range of fields of view with both square and rectangular aspect ratios (3:4 and 2:4) are used. Fields of view vary from $1/2^{\circ}$ to upward of 20°. Two (or more) discrete fields are normally provided for search and precision track/identification capability, respectively; continuous zoom capability is possible. Typical magnification ratios between narrow and wide fields of view vary from 3x to 6x. The horizontal scan rate (i.e., field rate) is generally 60 per second with some designs as low as 15 per second. Horizontal scan efficiency varies from 60 to 90 percent. Usually the horizontal scan is undirectional; however, bidirectional scanners have been developed (with nonlinear scan rates). Resolution varies from 1/8 milliradian to upward of 2 milliradians depending on field of view, optics, detector cell arrangement and signal processing.

The sensor assembly is mounted on a stabilized gimbal system which provides pointing and tracking capability. Gimbal orders and limits vary. Typical gimbal limits cover the frontal area from $+5^{\circ}$ to -35° in elevation and $+20^{\circ}$ to -20° in azimuth; in some configurations the gimbal ranges extend through 90° to permit target tracking for weapon guidance through impact. The FLIR video is suitable for video tracking; in fact advanced FLIRs have automatic tracking capability. In those designs in which the FLIR format is converted to a standard TV format, a conventional TV tracker can be used and shared with TV sensors (where FLIR/TV sensor combinations are used).

The FLIR signals available at the output of the detector cells are processed in various ways to produce a displayed image. One direct display technique ties each detector cell to a light generating cell (plasma, glow tubes, electroluminescence, light emitting diode) such that the light output is modulated directly by the detector cell signal. The light generating cells are arranged in an array similar to the detector cells and scanned horizontally in synchronism with the detector array to produce the apparent raster image. This image may be viewed directly through suitable optics. Alternatively, it may be viewed by a television camera whose output is a conventional TV format which may be displayed on standard TV monitors (and recorded on TV video tape recorders). An alternate direct display technique involves multiplexed sequential sampling of the vertical detector array (at a rate consistent with the desired resolution) to produce a serial video train in a vertical raster. The display image frame is generated by modulation of a synchronous vertical raster on a CRT. Typical multiplex frequencies are in the 10 to 30 megahertz region. Appropriate synchronizing signals and video gates are provided to the display. The multiplexed video may be written into a double-ended storage tube and read out in a standard TV raster for display on conventional TV monitors.

Finally, a third scan conversion system exists in which the multiplexed video is displayed directly on a small CRT in a vertical raster format which is viewed by a conventional TV camera. Typical scan converted FLIR formats are standard 525 line and 875 line TV rasters which provide a conventional horizontal raster output. In general, some loss of image quality occurs whenever FLIR video is scan converted, particularly by analog techniques. The dynamic range of FLIR detector signals is generally above 40 dB with 60 to 70 dB typical. Non-linear processing is sometimes used to match the transfer characteristics to the available dynamic range of the display.

The DISCOID FLIR concept is a recent development which generates IR imagery directly in a standard horizontal TV raster. In the DISCOID approach a short horizontal detector array is scanned through a TV raster (left to right, top to bottom) by rotating optical elements. The output signals of the detector cells are integrated with appropriate time delays to produce a serial video train representing IR signal intensity at each raster point. Video integration is required to produce the necessary effective sensitivity. Developmental DISCOID scanners with frame rates of 15 per second and interlace patterns of 2:1 and 4:1 have been built. Standard 525 line TV raster operation with 2:1 interlace and 30 frames per second is projected for the near future. DISCOID type FLIR sensors are under development for missile guidance seekers. Since most FLIRS are already scan converted and new FLIRS will be read out in a TV format, it is not reasonable to require digital scan conversion in the MMSDS system.

IR Line Scanners (IRLS)

Downward looking IR line scanners provide high resolution strip maps by scanning a detector cell or array across the flight path and recording the resulting video on film. Scan rates of 1000 lines per second are typical. Frame time varies as a function of coverage and aircraft speed; 10 seconds is a typical frame interval. Sensor coverage across track is in the ±70° range. Resolution is in the vicinity of one milliradian (or 1000 to 1500 elements per frame dimension). The basic dimensions of IRLSs are along-track-distance versus cross track angle. Image distortion results from this format — rectification is possible by appropriate display mechanization. Scan Conversion is required to store a line at a time and read it out in a TV format.

IR Search/Track Set (IRST)

Air-to-air IRSTs operate similar to FLIRs; however, the sensor arrays are limited to between two and eight detector cells, and the azimuth scan rate is on the order of 100°/sec. Multiplexing of the detector array is accomplished at a sweep rate of about 40 microseconds. The detector output signals are displayed as intensity and/or amplitude modulated cell traces in a C-scan format (elevation versus azimuth). Typical resolution is 1 milliradian. Multi-bar scan patterns similar to those of air-to-air radar search patterns are provided. The number of sweeps per bar depends on the azimuth coverage. Typical maximum values are around 2000 sweeps per bar. Azimuth expansion is required when maximum target discrimination capability is needed. IRST video is intensity modulated above an operator-controlled threshold level. Scan Conversion is required to display IRST video in a TV format. Audio tone signals are provided as a supplement to the visual IRST display presentations.

Television (TV)

Airborne TV sensors have been developed for long range target identification, precision tracking (using gated video trackers), missile guidance, low light level observation of terrain for purpose of flight control, general orientation, target detection, acquisition, tracking, identification and weapon delivery. Functionally, TV is similar to FLIR; however, its performance at low light levels is more limited. TV images are generally more readily interpretable due to the sensor response in the visible region.

Several television scan standards have been defined. The most common is the 525 line raster with 30 frames per second, 2:1 interlace and a 3:4 frame aspect ratio. Variations of the standards include: 525 line square rasters (missile televisions; e.g., Walleye, Maverick, Condor), 787 line raster, 875 line raster and up to 1200 line rasters. Video bandwidths vary from 5 to 20 megahertz depending on the raster formats. Dynamic range of the video is generally in excess of 24 dB with 30 dB typical. The effective resolution of the TV sensors is generally considerably lower than that implied by the number of raster lines. Typical resolution for 525 line rasters is in the 300 line range and high resolution TV's provide 600 to 800 lines of resolution (with approximately 1000 line rasters). The effective resolution of low light TV (LLTV's) varies with light levels. LLTV systems can provide 300 to 800 lines under relatively high levels but may be limited to 100 to 200 lines under extremely dark conditions.

Synchronizing signals may be provided by the TV with the video (composite video) requiring sync separation in the display, or they may be transmitted on separate lines. TV cameras may also be controlled by external sync signals provided by the display, data processor or other airborne sensors (e. g. , FLIR).

TV fields of view vary from $1/2^{\circ}$ (television sight unit for long range target identification) to larger than 40°. TV sensors are gimbaled and stabilized. Video tracker capability and slaving to other tracking sensors are typically included in the TV system design.

TV systems have been devised which use pulsed lasers for illumination of the object space. Typical laser pulse frequencies are in the 10 to 15 pulse per second range; consequently, illumination is intermittent relative to the standard 60 fields per second display refresh rate required for normal flicker-free TV operation. Video storage in the TV or display system is required. Standard TV formats and rates apply.

The Effect of EO Sensor Characteristics on MMSDS Design

The basic types of EO systems described above as well as the more promising advanced system types or configurations are included in the analysis of EO sensor parameters. Table 8 indicates the EO sensors that are analyzed as part of the multi-sensor-display analysis. A detailed tabulation of the EO sensor parameters is provided in Volume III. The sources from which these data were developed are given in Appendix A.

The object of the EO sensor display analysis is to identify the EO sensor characteristics and parameters that have an impact in the design of the multi-sensor display system. Of special concern are the EO sensor performance parameters that dictate the use of digital scan conversion. Table 9 presents a listing of pertinent EO sensor parameters that are analyzed for their possible impact upon the design of the multi-sensor display system.

It is concluded from this analysis that digital scan conversion is required for IRLS and IRST sensor modes. However, most operational FLIR systems are already scan converted to a TV format and the trend in future FLIR systems is to provide a direct TV scan. Therefore, scan conversion is not required. However, freeze capability of all or a part of the field of view (FLIR or TV) is desirable. Existing FLIR analog scan converters do not possess the freeze capability and direct TV sensors cannot be frozen.

TABLE 8. EO SENSOR LIST

EO System Type	EO Sensor Equipment	Airborne Vehicle Application
IRLS	AN/AAS-18	RF4-B, 4-C, 4-E
IRST	MA-1, AN/ASQ-25	F106-A, -B
FLIR	AN/AAR-37 NARBS FLIR	A-7E, P-3 Light Attack (A-10)
Television	LLLTV, TISEO, Walleye, and Maverick - covered by EIA STD RS 170 or RS 343-A	Varied

TABLE 9. EO PARAMETERS AFFECTING DISPLAY SYSTEM DESIGN

Parameter	Impact on Display Design
Format	Standard TV format sensors require freeze capability, non-TV format sensors require scan conversion.
Resolution	Affects memory size either for scan conversion or freeze.
Dynamic Range	Affects memory size, A/D converter requirements.
Aspect Ratio	Affects display format.
Scan Rates	Affects address generation requirements.

Since a television sensor is already in a television raster format, scan conversion is not required and the video can be displayed directly on the monitor. However, it is desirable to provide a freeze mode. This is particularly desirable for both TV and FLIR when the ratio of velocity to altitude is so high as to result in a smeared display. However, it should be noted that a single stored and displayed field will suffer a loss in S/N since frame to frame integration of the camera tube and eye are not experienced. The MMSDS should be designed to provide this freeze capability, but further study is recommended in order to determine its actual usefulness.

2.2.3 Symbology Requirements

In addition to the sensor video, the MMSDS must also generate and display symbology. This includes symbology for flight, terrain avoidance, navigation, target search, weapon delivery, and other functions. The symbology requirements vary widely for the aircraft and avionics systems covered by this study. The optimum repertoire and symbol shape is continually being updated to provide optimum performance. This is confirmed by the recent revisions in MIL-STD-884 (A, B, C). This standard is a joint Air Force, Army, Navy attempt to standardize symbology among services and aircraft. It should be noted that none of the existing avionics systems comply with this specification. Also, if and when this standard is imposed there will undoubtedly be revisions. Therefore, it is desirable to provide a symbol generation technique which can be easily modified and updated in the field.

Table 10 is a compilation of the symbol requirements as a function of mission mode and is a summary of the data from MIL-STD-884B. All or some of these symbols are required in the various systems covered by this study. As an example of how symbols are combined and displayed, Table 11 was compiled for the F-4 system. This is representative of the symbology used in present systems (e.g., A-7, F-106) as presented on a 5-inch sensor display. This symbology is broken into two groups. One group is generated in the symbol generator; the second group of symbology is received already mixed in with the sensor video.

Figure 2 is a representation of the symbol requirements for advanced weapon systems (such as B1). In addition to attitude information shown in display center, speed and altitude flight data are presented dynamically in the form of vertical and horizontal tapes along the edges of the display. The sensor video is presented in the center.

Since variable display sizes and raster structures are necessary to meet the diverse requirement of the MMSDS program, a symbol generation technique must be utilized to allow symbol programming to insure that symbols are presented with reasonable size and clarity. For alphanumeric symbology the symbols must be at least 0.2 inch high to be easily readable at 28 inches in the cockpit environment. This is the numeric size specified by MIL-STD-1472A. The symbology must also be sufficiently bright to allow reading in a high ambient and in some cases against the sensor video background. Capability for multiple gray shade encoding of symbols is also desirable since some studies indicate an improved symbol quality for in-raster symbols when using gray shades.

In conclusion, it can be seen that the symbol generation requirements for the MMSDS can vary from a simple repertoire to a very complex repertoire and indeed the size and shape of the symbols must be able to be modified to meet the variable raster requirements. This dictates the use of a flexible, programmable symbol generator technique.

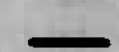
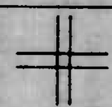
TABLE 10. SUMMARY, DATA DISPLAY REQUIREMENTS

Display Data	Data Representation	Take-Off	Naviga-tion	Terrain Following/ Terrain Avoidance	Search and Detection	Weapon Delivery	Landing
Heading	Horizontal Tape	X	X	X	X		X
Altitude	Vertical Tape	X	X	X	X	X	X
Vertical Velocity	Vertical Tape	X				X	X
Attitude	Pitch Ladder	X	X	X	X		X
Airspeed	Vertical Tape	X	X			X	X
Roll Angle	Horizontal Scale	X	X				X
Angle cf Attack	Symbol	X	X				X
Target Designate	Symbol		X		X	X	
Director	Symbol		X	X		X	
Velocity Vector	Symbol	X	X	X	X	X	X
Horizontal Line	Rotated Line	X	X	X	X	X	X
Navigation Steering	Horizontal and Vertical Lines		X				X
Sensor Elevation Angle	Symbol			X	X	X	
Slant Range	Alphanumeric word			X	X		
Aircraft Reference	Symbol	X					X
Closure Rate	Vertical Tape				X	X	
Armament Datum Line	Symbol					X	
Aiming Point	Symbol					X	
Bomb Fall Line	Line - vector					X	
Solution Cues	Horizontal line(s)					X	
Pull Up Cue	Symbol					X	
Weapon Release	Flash data					X	
Break Away	Crossed lines	X	X	X	X	X	X
Warning	Flash word	X	X	X	X	X	X
Ordnance Data	Alphanumeric word					X	
Terrain Contour	Line graphic			X			X
Runway Reference	Line graphic						X

TABLE 11. F-4 SYMBOL REQUIREMENTS

SCD Reference		Nomenclature	Symbol	Dimensions for 3.5 in. x 3.5 in.	X Position	Y Position	Input Signals	Scale Factor	Functional Description
3.12.4.1	①	Elevation strobe	—	0.25 ±0.05"	Fixed on right edge of display	±0.9375	+15 VDC → Top 0 VDC → Center -15 VDC → Bottom	4 degrees/volt	Indicates antenna position relative to level flight
3.12.4.2	②	Horizon line	— —	2.85 ±0.12 in. center third blanked 20 ±10 Mil thick	Roll ±90°	Varies with climb angle	Horiz-Cos Roll 0→28.3 VPP Horiz-Sin Roll at 900 Hz Climb-Cos Roll ±9.95VDC Climb-Sin Roll ±9.95VDC	0.292"/Volt	Indicates aircraft roll angle and pitch angle
3.12.4.7	③	Breakaway X	×	1.0 ±0.1" High 1.0 ±0.1" Wide	Center	Center	On → +28 VDC Logic Signal	N.A.	Appears at minimum launch range indicating discontinuing attack
3.12.4.5	④	Range Rate Circle	◯	3.06 ±0.06" Dia. Circle 1.9 ±0.4" Dia. to Bit 0.375 ±0.06" Gap Length	Center (Gap rotates) (Limits at -45°, +270°)	Center	-12 to +2 VDC (Usable Range) + → CCW - → CW ±24.5 VDC (Actual Signal)	22°/Volt	(Displayed during track) (The gap indicates closing or opening rates of target and interceptor). (Dia. reduction indicates when system enters track memory, HOJ, or manual track)
3.12.4.6	⑤	Steering Error Dot	■	Square 0.06 $^{+0}_{-0.02}$ in	Variable ±2.85"	±2.85"	±14.1 VDC Up and Right Positive	0.286"/Volt	Linear function or Az and El error from attack course. Used in track only.
3.12.4.4	⑥	ASE Circle	○	0.186" to 1.2" Dia.	Center (Dia. varies)	Center	0.655 → 4.2 VDC	Dia. 0.286"/Volt	Indicate allowable steering error for weapon delivery
3.12.4.8	⑦	RA Strobe	—	0.375 ±0.06"	Fixed on left edge of B sweep	Varies according to range scale and weapon	0 to 7.3 VDC positive up	Varies	Indicate maximum launch range of weapon selected
3.12.4.9	⑧	R_{MIN} Strobe	—	0.375 ±0.06	Fixed on left edge of B sweep	Varies according to range scale and weapon	0 to 7.3 VDC positive up	Varies	Indicates minimum launch range of weapon selected
3.12.4.3	⑨	Acquisition Symbol	| |	0.25 ±0.06 High 0.25 ±0.03 Width	±1.75" From Center	Positioned by time relationship between R gate and RDR trigger	±25V + Left	0.07"/Volt	Indicate position of the B trace and range strobe when the action switch is depressed to half action
3.12.4.10	⑩	Offset Cursor	|	3.5 ±0.06"	Variable in AZ	Fixed	±25V Positive Left	10 Mi 0.175"/V 25 Mi 0.07"/V 50 Mi 0.035"/V	Used as bombing reference
3.12.4.11	⑪	HOJ	H	0.25 ±0.06 High 0.25 ±0.06 Wide	Left & Right (Non Interference)	Top	28 VDC Logic On	N.A.	Indicates HOJ mode of operation (Home on Jam – Angle Tracking Jam)

Table 11. (Concluded)

SCD Reference	Nomenclature	Symbol	Dimensions for 3.5 In. x 3.5 In.	X Position	Y Position	Source	Functional Description
3.12.5.1	① Bombing range strobe or offset cursor		Approximates a true arc for an input true arc of radius 3.466" displayed arc shall be within radii limits of 3.43" and 3.50"	Full screen width	Adjusted using ground	Radar Video	Represents a predetermined horizontal range at a given altitude. As offset cursor symbol becomes vertical line to indicate the azimuth position of radar IP and/or target
3.12.5.2, 3.12.5.3	② Range strobe		Short horizontal bar brighter than any other displayed radar information. Vertical thickness of bar depends on range scale and is 0.4 ±0.02μ sec wide in time.	Centered with respect to target acquisition symbol ±0.02 In.	Determined by range gate pulse leading edge position relative to radar trigger leading edge	Radar Video	Indicates target range in track
None	③ TV mode crosshairs		Parallel lines cover full screen	Centered	Centered	TV Video	Indicates strike position of weapon

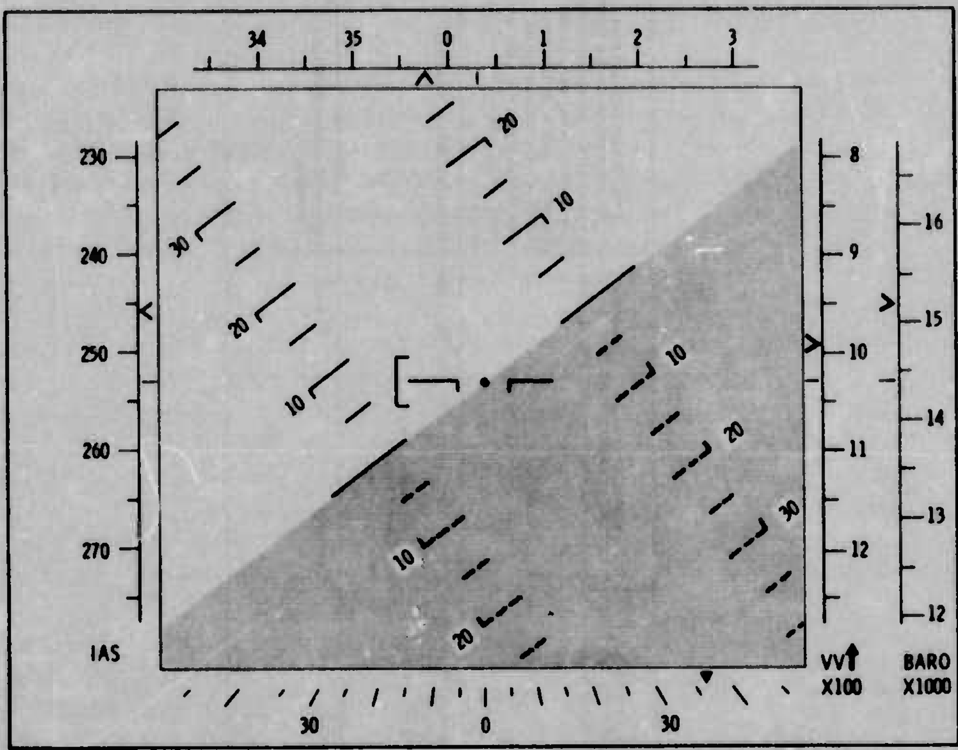


Figure 2. Symbology for advanced system application.

2.2.4 System Interface Requirements

The input interface to the MMSDS consists of mode control, video, timing and symbol generator signals. The mode control signals define the display format, coverage, sensor mode, etc. Input video is received from the various on-board sensors. Timing signals define the position of the sensor video with respect to the scanned space. Discrete and dynamic signals are also received to define the proper generation of the symbology to be displayed. Two types of input interface are discussed in this report, the DAIS interface and non-DAIS interface.

The output interface from the signal transfer unit to the display is a single composite video line. The justification for this interface is presented in Section 4. It provides a simple interface to multiple displays and to a video recorder.

In addition to the electrical signal interfaces, the physical interface must also be considered. The signal transfer unit and display units, if separated, must be housed in either an electronics bay or in the cockpit. As such, for maximum multi-system commonality, modules must be designed which will fit into the O & M constraints of the various systems.

DAIS Interface

The baseline modular display system design is based on compatibility with the DAIS system interface. DAIS (Digital Avionic Information System) is an Air Force concept whereby all avionic subsystems are treated as a whole system rather than as a conglomerate of independent equipments. A major feature of DAIS is the use of a multiple terminal data bus. All avionics control, test, and mode information will be transmitted on this bus. Therefore the mode control, sensor data, and test command signals for the modular display system will be received over this bus. Furthermore, results of built-in-test for the display subsystem will be transmitted back over this bus as static words.

A block diagram of the DAIS Data Bus Architecture is given in Figure 3. The modular multisensor display system appears in the diagram as a subsystem coupled to the twisted pair transmission line by a Multiplex Terminal Unit (MTU) and a Subsystem Interface Unit (SSIU). Flow of data on the twisted pair data bus is controlled by the data bus controller. This controller would be a part of the aircraft main computer.

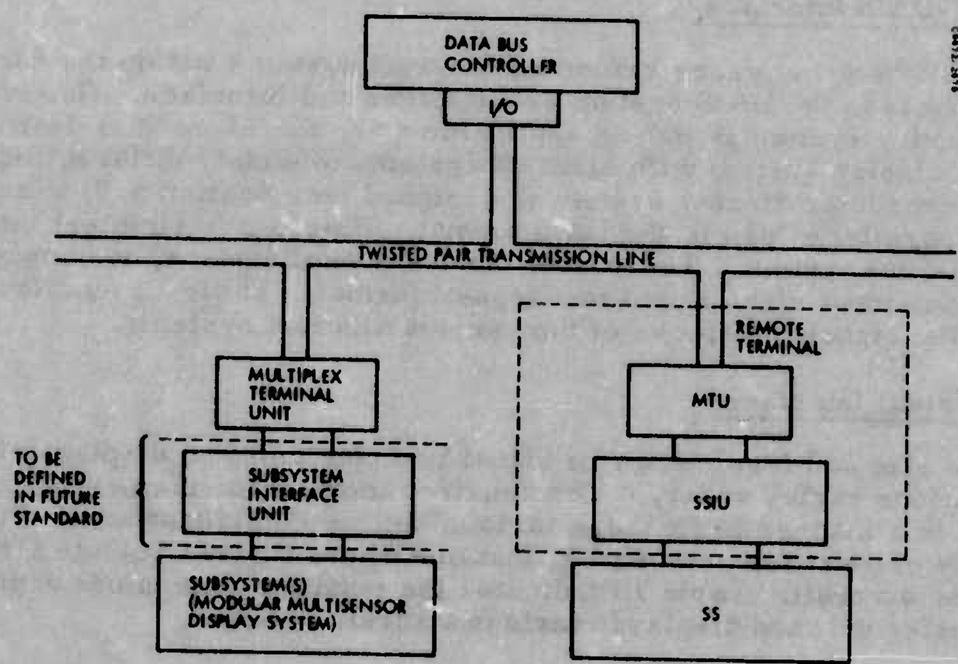


Figure 3. DAIS data bus architecture.

Three 20-bit word types are defined for the bus – a data word, a command word, and a status word. Each of these words consist of 3 bits for synchronization, 16 bits for address, data, or error codes, and 1 bit for parity. These words move serially on the bus at a 1-MHz rate.

Each MTU is assigned a unique address in the command word and responds when addressed by receiving or transmitting data and status words. The MTU performs the necessary serial to parallel and parallel to serial conversions to interface between the serial data bus and the parallel lines to the SSIU. The MTU receives and stores a complete data message (up to 32 16-bit words) before retransmitting the message as a block to the SSIU. The SSIU in turn sends the message on to the subsystem. Although the SSIU is not completely defined, it is logical to expect its output to be 16 bit parallel words with a few additional control lines. This is the interface provided for in the modular multisensor display design. Eighteen parallel lines are provided for a 16-bit word and two control lines to connect the display system with the SSIU.

The SSIU and MTU are considered to be parts of the subsystem terminals. Therefore, design of the SSIU and MTU are not a part of this study.

Non-DAIS Interface

It will be many years before all aircraft systems within the Air Force command possess the DAIS system architecture and interface. However, the modular display system is indeed applicable now, therefore it is desirable to couple this display system with aircraft systems of widely different interfaces. The modular display system is designed (see Section 5.0) to accept the digital parallel words in the DAIS format. This is the simplest interface for an all digital system. Therefore, for other applications, it is necessary to convert the input signals into this type of format. Table 12 functionally describes the signal interfaces of the various aircraft systems.

2.2.5 Physical Interface

The size and form factor of signal transfer unit and display unit for the applications varies widely. The required module complement must be configured in a manner to fit these various outline configurations. This is particularly critical for retrofit applications where a given volume already exists in the aircraft. Table 13 indicates the existing dimensions of the signal transfer unit and display in various aircraft systems.

TABLE 12. NON-DAIS ELECTRICAL INTERFACE SUMMARY

	Mode Control Signals	Antenna Position	Symbol Signals	Video
F-4 Series Aircraft	25 Discrete Signals 28 vdc	Azimuth ±15 v Signal (0.25 v/deg)	18 Analog signals define symbol position (approx 25 v)	Analog (with prf pulse)
F-106	14 Discrete Signals 28 vdc	Azimuth 100 v p-p dc	18 Analog signals define symbol position (approx 100 v)	Radar 2 v (with prf pulse) IR 9 v
F-15	20 bit Serial Digital Data (TTL level)	20 bit Serial Digital Data (TTL level)	N. A.	2 bit digital with transfer clock
F-111 Series	26 bit Serial Digital Interface w/Computer TTL level	Serial Digital Interface	Serial Digital Interface	Analog video
A-7	20 bit Serial Digital from Computer — Discrete 28 v Signals from Radar	Demodulated Analog Signal	Serial Digital Signals from Computer, Analog signals from Radar	Bipolar analog video with sync pulse
F-5E	7 Discrete Signals 28 vdc	Analog Azimuth Signal	Analog Position Signals	Composite analog video

TABLE 13. INSTALLATION O & M

	Digital Signal Transfer Unit, in.	Display Units Size of Unit, in. (w x h x d)
F-4	8.2 x 10.3 x 20.3	Rear – 6.5 x 8.5 x 18.0 Front – 11.5 x 6.77 x 18.9
A-7	9.5 x 6.5 x 18.0 (half is available for scan converter functions)	5.75 x 5.75 x 17.25
F-106	7.7 x 11.7 x 13	7" diameter x 25"
F-15	6 x 8-1/2 x 14	6 x 6 x 15
F-111	8 x 12 x 20	VSD 8 x 7 x 27 MSD 14 x 11 x 32
F-5E	None	6 x 6 x 17

2.3 Operator Requirements

Sensors that map the ground provide display images that are used by the aircrew to find, recognize, and locate targets or landmarks. The display designer is charged with selecting, within the framework of physical and cost constraints, those display characteristics that enhance the crew's performance of those tasks. Assuming ideal, well trained crewmen, the design of displays optimized for these tasks must satisfy two major operator derived criteria: 1) the displays must present data that can be seen, that is, the displayed data must exceed visual thresholds, and 2) they must, in conjunction with the sensor, meet the cognitive demands of the operator, that is, the display/sensor system must provide the information the crewman needs to carry out the task in hand. The performance effectiveness of a display, then, may be assessed against two classes of behavioral criteria: those related to the psychophysical demands of the operator and those related to the cognitive demands of the operator.

2.3.1 Psychophysical Demands

The non-time varying psychophysical demands can be met by matching the display to the modulation sensitivity function (MSF) and luminance dynamic range of the eye. The visual MSF describes the response characteristics of the eye as a detector and typically describes that response as a function of spatial frequency, modulation, display luminance, target subtense, and visual adaptation level.

An optimum display design is one that provides a minimum resolution density or a minimum number of resolution picture elements (pixels) per unit length while conveying the necessary information to the observer. The minimum number of raster resolution elements in a real-time display application is dictated by the number that permits the required comprehension rate of the data presented. It is presumed that, for rapid comprehension, the pattern or granularity resulting from the discrete nature of the elements forming the image must not be objectionable. To estimate the point at which the discrete nature becomes objectionable, one must consider the visual response of the human observer. The most sensitive spatial frequency for the human observer is 5 to 7 cycles per degree (see Figure 4). Thus any structure such as pixels or scan lines will be highly visible at that value. The 50 percent point has been chosen as a value for which regular structure ceases to be visibly objectionable; this corresponds to a spatial frequency of 18 cycles per degree. (Ref. 1)

Two viewing distances are typical for cockpit displays: 30 inches, which corresponds to the nominal task eye position and 20 inches, which corresponds to a vigilant condition. Resolution of 18 cycles per degree is equivalent to 36 pixels per degree. Referring to Figure 5, it can be seen that the most demanding condition for resolution density occurs when the pilot is in the vigilant viewing position (20 inches) corresponding to 104 pixels per inch. On this basis, 100 pixels per inch is a reasonable value to use in order to rid a display of visually objectionable pixel or raster structure.

The total resolution of the display is the product of the resolution density and display size. The resolution density was selected based upon the criteria that the discrete nature of the display must not be objectionable at the closest viewing distance. The total resolution or the number of pixels across the display width is also matched to the capabilities of the signal source or sensor. In matching the sensor resolution to the display resolution, one must consider not only the number of elements but also the phase relationship between the display and the sensor elements. If the display is synchronized to the sensor and if there is a one-to-one relationship between the elements of the display and the elements of the sensor, a display results that is isomorphic to the sensed imagery. A display isomorphic to a scan converter of 1000 x 1000 elements, would contain 10^6 pixels.

<u>Hue</u>

The MSF data used in these analyses (fig. 2) were gathered from laboratory studies that used test displays with greenish-white phosphors. This means that they were operating in the portion of the spectrum where

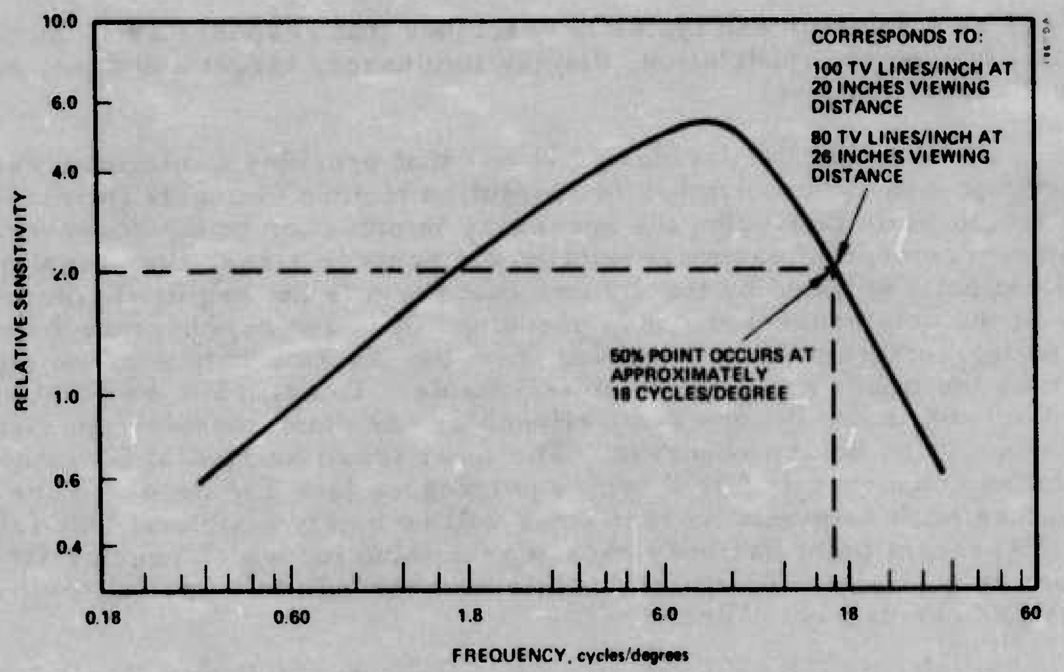


Figure 4. Modulation sensitivity function of human visual system.

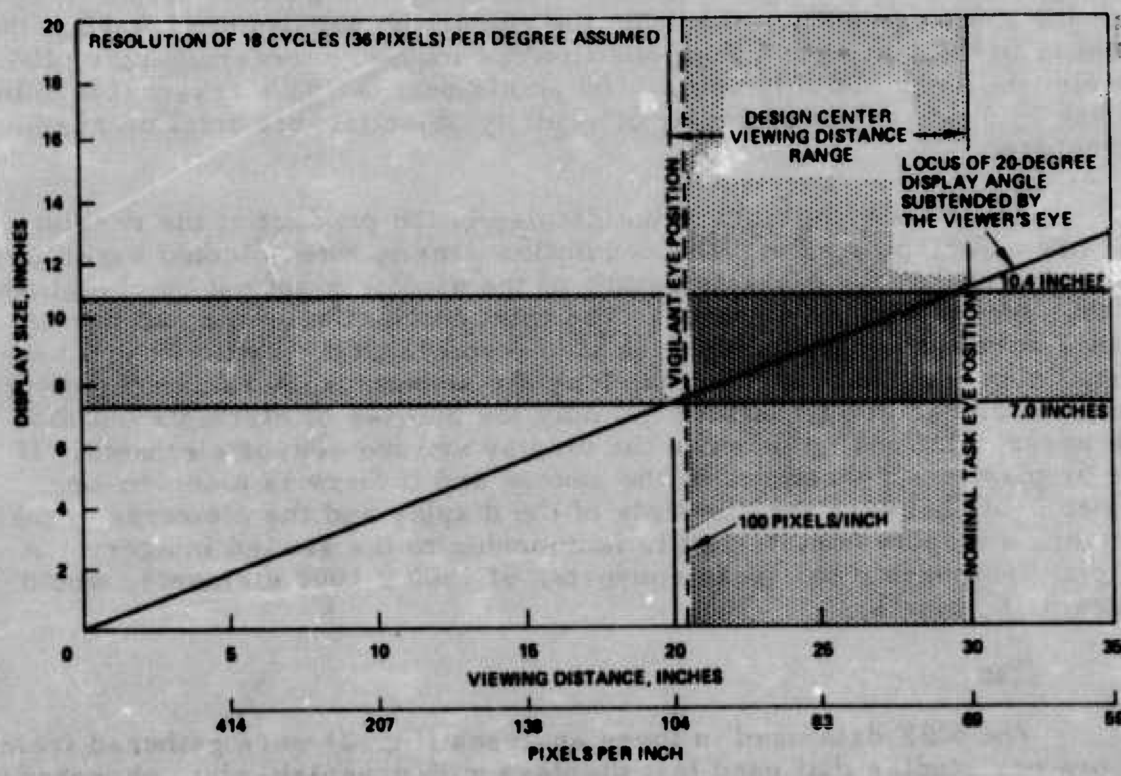


Figure 5. Optimum display size and resolution density as a function of viewing distance.

the luminous response of the eye is most sensitive. Operational displays may or may not have phosphors of that hue, and the consequence of using other colored phosphors should be considered. Figure 6 taken from Semple (ref 2) illustrates the differential sensitivity of the eye to the wavelengths contained in the visible portion of the spectrum. Also shown for comparison are the emission wavelengths of some common CRT phosphors.

As can be seen in Figure 6, more energy is required to produce the same effective display luminance at the extremes of the visual spectrum as compared to the center. It is the photopic or cone response that is of prime interest since foveal (cone) vision is required to extract information from the display. The peak of the photopic response is seen to occur at 555 millimicrons which is the green-yellow portion of the spectrum.

There are reasons other than luminous efficiency for selecting a phosphor near the center of the photopic curve. The use of red light in pattern perception presents problems in chromatic adaptation and increased accommodative fatigue due to ocular chromatic aberration. Chromatic aberration effects decrease the resolving power of the eye and thus would increase the visual demand curve or display contrast required. Semple (ref 2) states that "the resolving power in the area of yellow-green wavelengths is almost equal to that of white light. For red, however, the resolving power of the eye is only about one-third as good as for white light and for blue it is only about one-fifth as good as white." These refractive deficiencies in the lens of the eye are most severe at low luminance levels due to the increase in the pupil diameter. Increased accommodation times may be required to focus red or blue light on the surface of the retina, and this would further degrade performance.

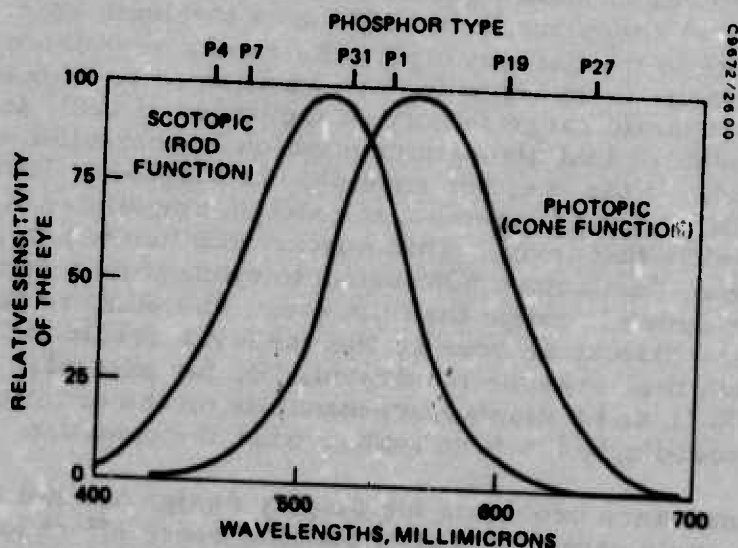


Figure 6. Spectral sensitivity of eye compared to commonly used CRT phosphor wavelengths.

Due to the combination of reasons described above, it is recommended that the phosphor selected lie in the green-yellow region of the visible spectrum. The P-31 and narrower band P-44 phosphors for example meets this requirement.

Traditional night use of monochromatic red colored light in CRT displays has been directed toward the preservation of dark adaptation. Since the rod receptors are relatively insensitive to the red area of the spectrum, red lighting has been used to preserve rod sensitivity. However, there is some argument as to whether red actually buys anything, and the Air Force has now gone to blue-white cockpit display lighting. A research review conducted at Hughes under another contract indicates the need for a revision of the long standing design principle that red displays should be used for night operations. Several of the reviewed studies have shown that visual tasks which require pattern recognition and thus foveal viewing, such as those projected for multi-sensor display application, do not benefit substantially from red light, either during preadaptation or when red light is the illumination source.

Luminance Dynamic Range

The modulation sensitivity function describes the amount by which a base level luminance must be changed in order that an adjacent luminance will appear as a different brightness to an observer. In order to know how much intensity information can be communicated by a display, one must know not only the modulation sensitivity of the eye as described in previous paragraphs but the luminous range over which vision operates. The number of perceivable gray shades, then, would be the luminous dynamic range divided by the number of discernible luminous differences. It is of some interest, therefore, to know the total luminance range of the eye. The total range is enormous if one considers the luminance of snow in the sun to the values of the darkest night. As can be seen from Figure 7, the total dynamic range is on the order of 10 billion to 1. However the instantaneous dynamic range is only on the order of 100:1 to 1000:1 and provides a window of that size whose position is controlled by the visual adaptation level. If the eye, for example, is adapted to 1000 fL, then any luminance below 1 fL will appear black and no brightness discriminations can be made below that level. This observation has two implications for displays. One is that it makes no sense to attempt to design displays that have a greater dynamic range than the eye. The other is that the average luminance of the display as seen by the observer should fall within the window to which the observer is adapted. If, for example, the observer is adapted to 2000 fL and a display luminance is on the order of 2 fL the image will appear exceedingly black no matter what the contrast.

The luminance problems for display design are not currently ones of exceeding the eye's capability but of bending every effort to extend the display average luminance and dynamic range. The greater the luminance the more likely will the display match the adaptation level of the observer in daylight conditions, and the greater the display dynamic range — up to the limits of vision — the more intensity information can be conveyed by the display.

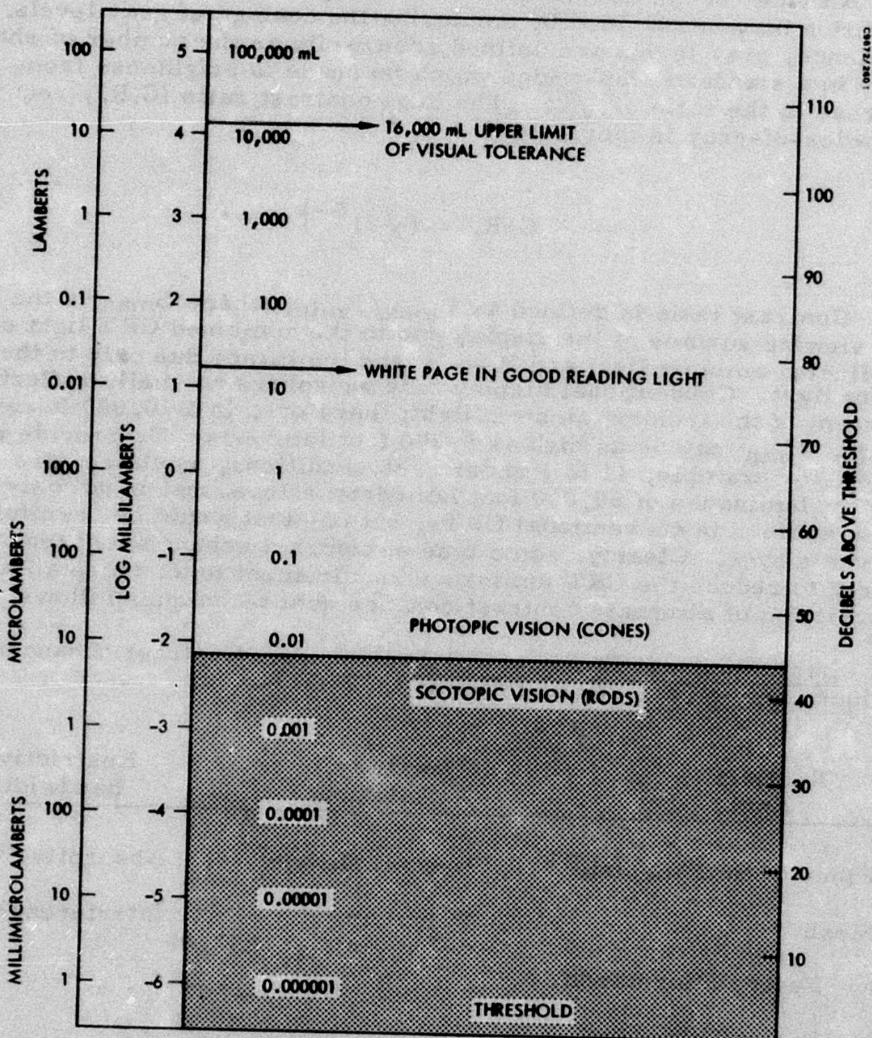


Figure 7. Range of light intensities that the human eye confronts (from Stevens, Ref. 3).

An index of the effectiveness of displays in providing intensity information may be obtained by employing the concept of gray levels. For convenience, gray levels are defined arbitrarily as the number of shades-of-gray in a standard step-wedge which increase in brightness from adjacent step areas in the ratio of $\sqrt{2}$. The total contrast ratio (C.R.) required for "N" shades-of-gray is therefore:

$$C.R. = (\sqrt{2})^{N-1}$$

Contrast ratio is defined as B_{max}/B_{min}, where B_{max} is the luminance at the viewing surface of the display due to the combined CRT light output and the reflected ambient light and B_{min} is the luminance due only to the reflected ambient light. Conventional display tube phosphors normally reflect 60 to 80 percent of the incident ambient light; therefore, in a 10,000 ft-candle ambient, B_{min} may be as high as 8,000 foot lamberts. To provide a contrast ratio of, for example, 11 to 1 under such conditions, would require a CRT high light luminance of 80,000 foot lamberts; a level that is not only impossible to achieve in conventional CRTs, but one that would be harmful to the observer's eyes. Clearly, some type of contrast enhancement technique is required to reduce the CRT luminance requirement to an acceptable level. A description of alternate contrast enhancement techniques follows.

Basic Contrast Enhancement Techniques. Contrast enhancement techniques may be classed as follows:

Restrictive Angle	Two-way Attenuation	Restrictive Bandwidth
1. Fiber Optic Faceplate	1. Neutral Density	1. Absorptive Filters
2. Mesh	2. Polarizing	2. Interference Filters
a. Kaiser Micromesh		
b. Hycon Thin-Film Multimesh		
c. 3-M Film.		

Specific contrast enhancement hardware often uses a combination of two or more of the above techniques. For example, an absorptive-bandwidth-restrictive-filter also uses neutral density two-way attenuation, attenuating frequencies inside and outside its pass band.

The analysis which follows first determines the advantages, disadvantages and characteristics of each individual technique used separately. Finally, combinations of the techniques are considered and evaluated.

Restrictive Angle Filters. All of the filters (techniques) grouped in this category utilize the fact that the operator need only observe the CRT light output over a limited viewing cone, while ambient illumination, on the average, will encompass an approximately hemispherical volume around the observer. A common example of the directional filter technique is the use of a hood over an oscilloscope to reduce the effects of directional room ambient.

1. Fiber Optic Faceplate

Operation of a fiber optic faceplate is illustrated in Figure 8

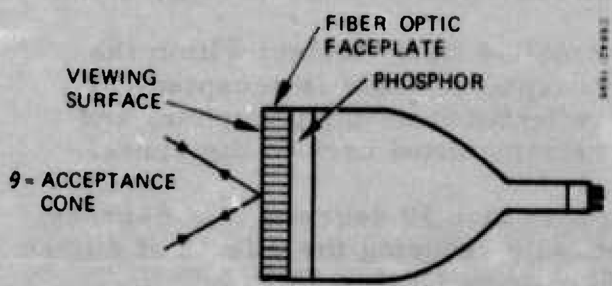


Figure 8. Fiber optic CRT.

Each individual fiber or light pipe is coated with a black material (EMA, Extramural Absorption material). Each fiber efficiently transfers all of the phosphor light that occurs within the fiber's cone of acceptance to the outside of viewing surface of the CRT. The light emanates from the CRT face with a similar cone of acceptance. To view the display, the observer must be within this acceptance cone.

Ambient light impinging on the CRT face outside of this acceptance angle is absorbed by the EMA coating. Since no light diode action is possible, ambient light incident within the angle of acceptance is passed through the fibers, reflected off the phosphor, and transmitted back to the viewer.

The effectiveness of a fiber optic faceplate can be approximated by assuming a diffuse ambient. The proportion of the ambient light rejected by the fibers is proportional to

$$\left(\frac{180}{\theta}\right)^2,$$

where θ = acceptance angle of the fiber. For a typical fiber optic CRT, $\theta = 80^\circ$ then

$$\left(\frac{180}{80}\right)^2 = 5.$$

Ignoring first surface reflections and phosphor reflection, a theoretical improvement in contrast ratio of 5 to 1 would result.

2. Mesh

The next general category of directional filters uses a thin mesh in front of the CRT where the mesh functions much like an in-line venetian blind as illustrated in Figure 9.

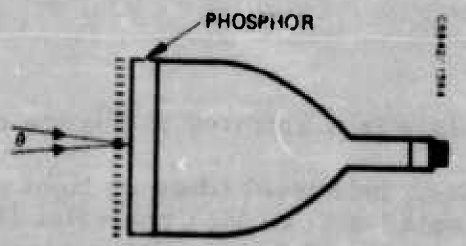


Figure 9. Mesh Type Filter

In this type of filter, light from angles outside the acceptance angle is absorbed within the louvers of the mesh. The acceptance angle is determined by the geometric construction of the mesh (depth, spacing, etc.).

Ambient light incident within the acceptance angle is accepted, reflected from the phosphor, and retransmitted back to the viewer.

Typical acceptance angles of less than 50 degrees (±25 degrees) can be obtained, thus theoretically reducing the effects of diffuse ambient by more than $(180/50)^2$ or more than 13 to 1.

The acceptance cone can be channeled to be other than normal to the CRT to accommodate an cff-axis viewer. Also, the louvers at the extremities of the display can be "focused" inward to prevent darkening of the display near the outer edges.

Two Way Attenuation. The next general category of contrast enhancement techniques takes advantage of the fact that ambient light has to pass through serial elements twice, while the CRT light output need traverse the optical chain only once, as illustrated in Figure 10.

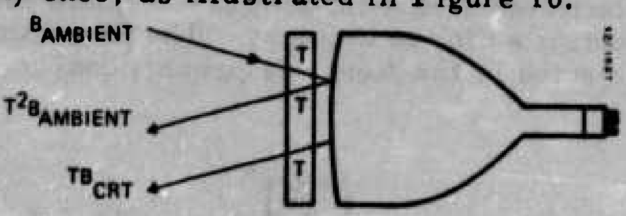


Figure 10. Two-way attenuation.

Ambient light is attenuated by T^2 (assuming 100 percent phosphor reflectivity), whereas CRT light output is attenuated only by T. Thus the theoretical gain is

$$\frac{\text{Brightness of CRT}}{\text{Ambient Brightness}} = \frac{T\,B_{CRT}}{T^2\,B_{Ambient}} = \frac{1}{T} \times \frac{B_{CRT}}{B_{Ambient}}.$$

This is a net gain of $\frac{1}{T}$ over the use of no series-attenuating filter.

Practical considerations (e.g., first surface reflection) reduce the gain possible with this technique to less than 10:1. There are two major types of two-way attenuation filters:

1. Wideband

   The most commonly used technique is the neutral density (gray) filter, a wideband filter which attenuates most frequencies uniformly. Neutral density filters are readily available in a wide variety of attenuation coefficients from a fraction of a percent to over 90 percent.

2. Polarizing Filters

   The operation of a polarizing filter is illustrated in Figure 11.

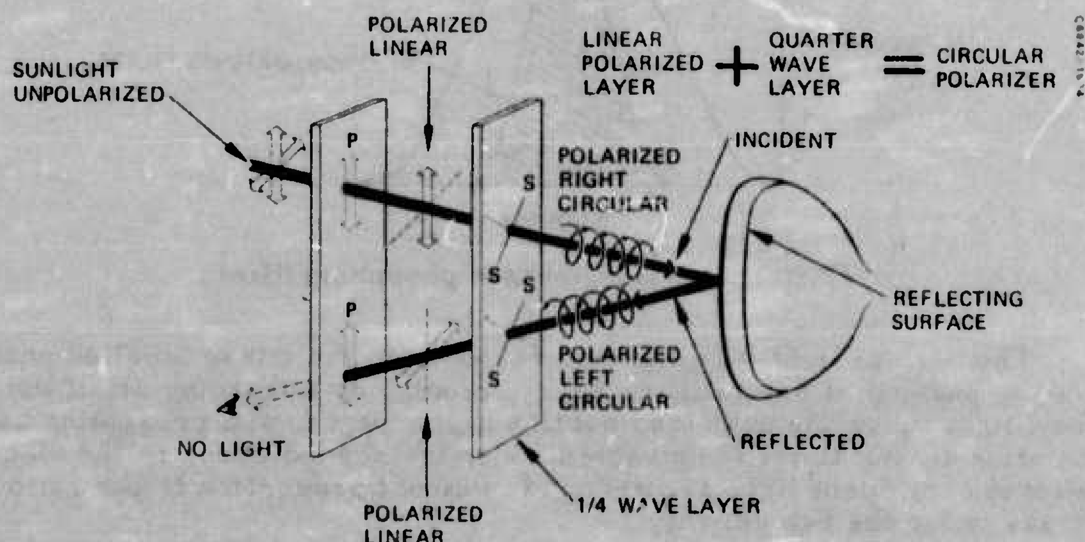


Figure 11. Circular polarizer.

The first surface linearly polarizes the incident ambient. The 1/4 wave layer polarizes the light right-circular. After specular reflection, the light is polarized left-circular, then is shifted 1/4 wave as it passes again through the 1/4 wave layer. The total change in phase to this point is one-half of a wave length, which transforms the ray to be linearly polarized into a plane 90 degrees to the original entry. This shifted light is then absorbed by the first element, the linear polarizer.

One principal disadvantage of using the circular polarizer directly in front of the CRT, is that phosphor will depolarize from 65 to 85 percent of the reflected light, thus the polarizer loses much of its effectivity. Polarizers are available which transmit from 20 to 40 percent of incident light, so the filter can also function as a neutral density filter.

The polarizer is designed for one specific center frequency (which matches the 1/4 wave retarder) so some leakage occurs at higher and lower frequencies. However, the polarizer is useful in front of an interference filter. Since the interference filter specularly reflects rejected frequencies, the polarizer can then efficiently absorb these polarized wavelengths.

Restrictive Bandwidth. The restrictive bandwidth filter passes all those frequencies within its own passband and attenuates those frequencies outside its passband. When combined with a narrowband phosphor as shown in Figure 12, the phosphor/matched filter combination provides a narrowband light output to the viewer.

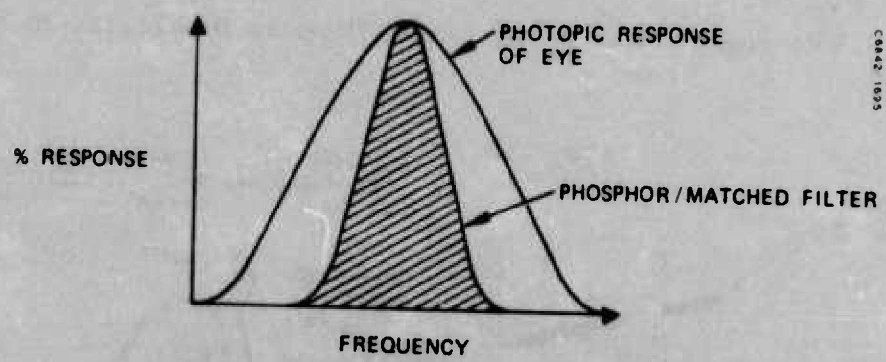


Figure 12. Narrowband phosphor/filter.

The normal light-adapted-eye responds to the curve labelled photopic response, peaking at 555 millimicrons (green). By absorbing all of the ambient light under the unshaded portion of the curve, and presenting useful information at only those frequencies under the shaded curve to the viewer, the effects of ambient light are reduced in direct proportion to the ratio of the areas under the two curves.

Two types of filters can provide the narrow bandpass required.

1. Absorption

   The absorption filters, which absorb the rejected frequencies, are not as efficient (10-30 percent transmission for the pass frequencies), nor are their passband curves as sharp as interference filters. Generally, they cost less than interference filters.

2. Interference

   The interference filter, which reflects rejected frequencies, typically transmits 80 percent of the center pass frequency, has sharp and narrow skirts on the nearly square frequency response curve, and generally is more expensive than an absorptive filter.

Absorption filters have no colorshift with viewing angle, whereas the passband of the interference filter is dependent on the angle of incident light. To exploit this angular dependence of an interference filter, consider Figure 13. This filter is designed for on-axis viewing (0 degrees) of a narrowband phosphor (such as P44). Light incident at angles greater than ±10 degrees is completely attenuated. The filter thus functions both as a narrowband filter and as a restrictive angle filter.

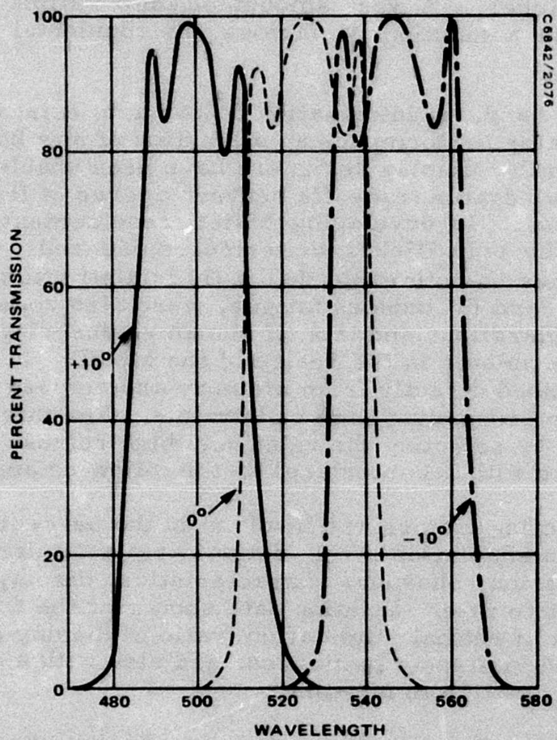


Figure 13. Angular dependence of interference filter.

Laboratory measurements and analysis here show that the maximum contrast enhancement technique is achieved by using both a two-way attenuation filter and a bandwidth restrictive filter. This is the filter combination recommended for the MMSDS.

Temporal

The above was a discussion of the spatial and luminance response of the eye. The ability of vision to discriminate temporal events is, for display design, generally handled under the heading of flicker or display frame rate.

The design requirement for display frame rate has traditionally been determined by the conditions under which a display operator will cease to perceive flicker. Perceived flicker, or the lack thereof, is measured by the critical fusion frequency (CFF). The CFF is defined as the frequency of change in the luminance of a visual stimulus at which perceived flicker extinguishes and a smooth fusion occurs. The design value typically selected for frame rate correspondingly has been that at which the CFF has been exceeded. In other words, the design philosophy has been that the display shall not flicker. A vast amount of information exists on the value of the CFF as a function of various environmental and display parameters.

On the other hand, no information is known to exist which quantifies degradation in operator performance as a function of how badly a display flickers. Consequently, display designers have been unable to make reasonable and knowledgable tradeoffs between degree of flicker and operator performance. In developing MMSD requirements, the CFF threshold was not the only flicker criterion considered. The point at which flicker becomes so noticeable that it (1) is distracting (2) begins to affect performance, and (3) induces fatigue, were also considered. Fortunately these considerations and lack of human engineering data did not constitute serious problems in the design of the MMSD. In this application, the display is refreshed directly from memory and refresh rate is relatively independent of other processing time constraints. For this reason, flicker could be eliminated by selecting the relatively high refresh rate of 60 Hertz (30 Hertz frame rate with 2:1 interface) as the following analysis will show.

Many interacting factors are involved in the perception of flicker. These include: light adaptation level, retinal area stimulated, luminance intensity, flash duration, phosphor characteristics, display refresh rate, and information update rate. Existing data show that the CFF increases with increased area of retinal stimulation (ratio of display size to viewing distance), increased in display luminance, and also with a decrease in duty cycle (ratio of on-time to off-time).

Figure 14 from Carel (ref 4) presents data that show the relationship of a number of these factors to the CFF. To illustrate the use of this figure, assume a maximum CRT brightness of 1000 foot-Lamberts (worst case) and a 10 percent neutral density filter giving an effective maximum display brightness of 100 foot-Lamberts. No display will ever be all maximally driven at the same instant because no information is transmitted in that mode; thus an average brightness for the entire display of 50 foot-Lamberts is a more reasonable value to select. The appropriate value of viewing ratio, ρ, (the ratio of viewing distance to screen diameter) lies in the range of 4 to 5 for the MMSD. It was desirable to use the standard TV refresh of 30 frames/sec with 2:1 interlace. Thus, following the value of 60 on the ordinate of Figure 14 across to intersect a value for $\bar{B}_c$ of 50 foot-Lamberts shows that a minimum value of t/T of 0.35 must be used to eliminate flicker from the display. Continuing the calculation, t = 0.35/60 = 5.85 msec. This value of t is the time required for the phosphor brightness

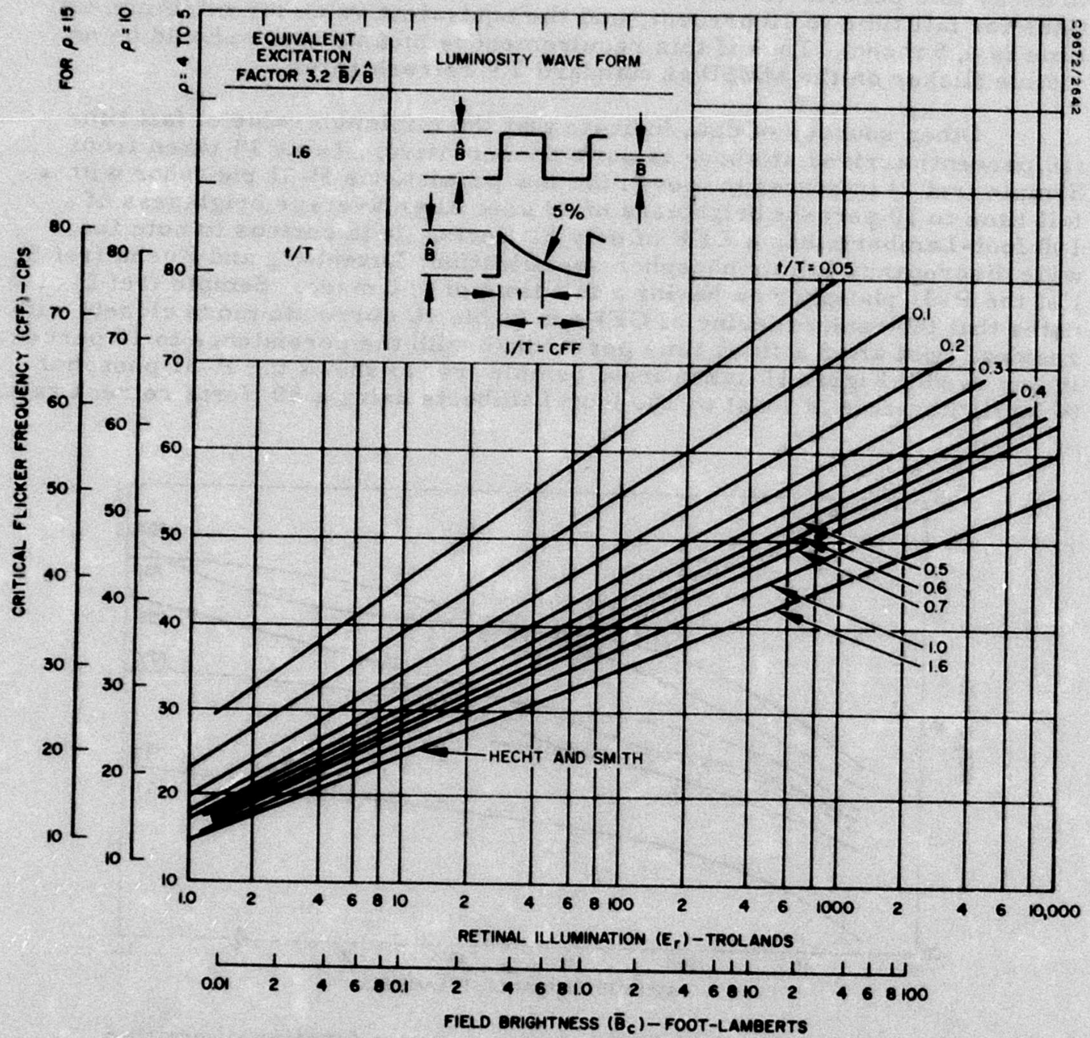


Figure 14. Threshold flicker values for intermittent illumination.

to decay to 5 percent of its peak value. Most phosphors are given specifications for fall time to 10 percent, and the equivalent value for minimum fall time is 4.5 msec. Thus if this requirement is meant, there should be no visible flicker on the MMSD at standard TV refresh rates.

Other sources of data indicate that the minimum value of fall time (10 percent) arrived at above is quite conservative. Table 14 taken from Semple (ref 2) indicates that even the low persistence P-31 phosphor with a fall time to 10 percent brightness of 38 μsec at an average brightness of 100 foot-Lamberts has a CFF of only 51 Hertz. It is curious to note the wide discrepancy in this phosphor specification; Luxenberg and Kuehn (ref 5) list the P-31 phosphor as having a fall time of 1.2 msec. Semple (ref 2) also notes that the rank ordering of CFFs in Table 16 correlate more closely with residual light after a fixed time period than with the persistence to 10 percent. In any event, Figure 15 taken from Semple (ref 2) shows the P-31 phosphor to be flicker-free at least to 100 foot-Lamberts using a 50 Hertz refresh rate.

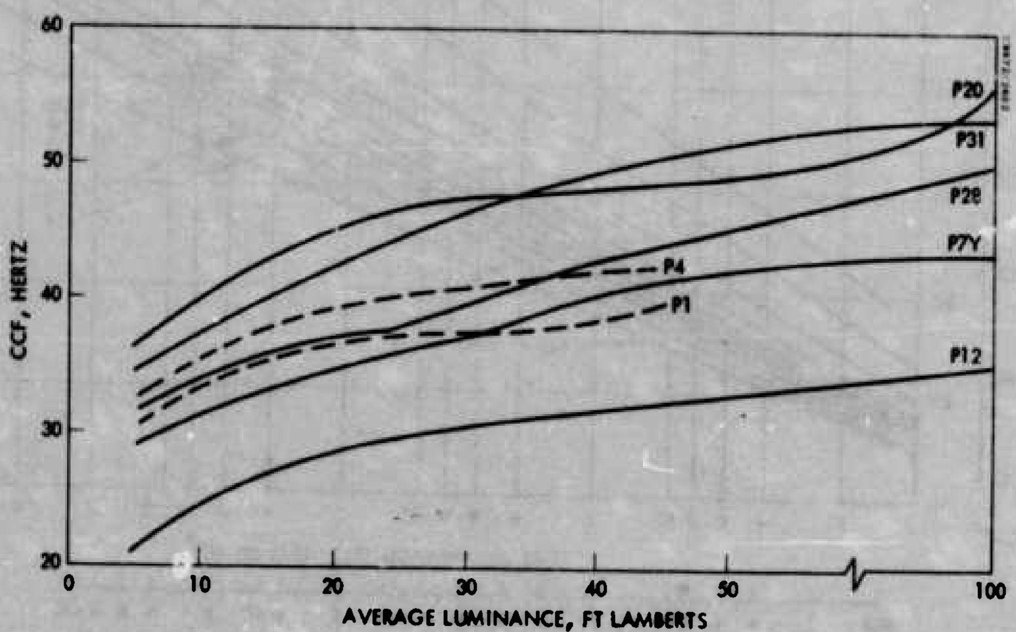


Figure 15. Critical fusion frequency as a function of emitted luminance and phosphor type. (Adapted from Turnage, Ref. 6).

2.3.2 Cognitive Demands

In the previous section, the response of the eye to intensity modulation and temporal interruption as a function of a select set of variables was described. These data inform us only of the conditions under which elements of an image may be visually discriminated without bothersome flicker. To

TABLE 14. CFF AND PERSISTENCE RATES FOR A NUMBER OF COMMONLY USED PHOSPHORS

Phosphor	Residual Light after		Persistence to 10%, sec	Empirically Determined CFF (small fields), cps					
				Turnage (1966)			Bryden (1966) 50 fL	Mitchell & Resnick (1960)	
	1/30 sec	1/60 sec		10 fL	32 fL	100 fL		10 mL	50 mL
P28	85	90	550×10^{-3}	34	40	46	31.4		
P19	80	90	220×10^{-3}				17.5		
P12	70	85	210×10^{-3}	25	29	32			
P7 (Y)	45	80	400×10^{-3}	32	38	43	29.8 (B&Y)		
P1	4	23	24.5×10^{-3}	33	38	43	29.2	32	38
P4	1.3	7	60×10^{-6}	35	41	47	33.5 (B&Y)	36	43
P31	<1	<1	38×10^{-6}	37	44	51	32.4		
P20	<1	<1	50×10^{-6} to 18×10^{-3}	40	47	54	32.7		

derive meaning or intelligence from an image the operator needs, of course, to make these discriminations. But in addition the target needs to be resolved both spatially and by modulation gradations, the sensor field of view (the context) must be adequate, and time available to extract the information must be long enough for the task at hand. The granularity of the spatial and intensity information, the amount of context, and the time required for different kinds of recognition tasks has been called the cognitive demand.

For completely analog systems, the MTFA is presumably an index correlated with the observer's ability to extract information about the sensed object space from the display. For quantized systems, no readily applicable model is at hand.

In quantized displays, pixels are picture elements — like the individual stitiches in needlepoint or a sampler that, taken together, form a picture. How many stitches does it take to define a rose? a face? or an armoured personnel carrier? How fine should the stitches, the pixels, be? If the picture is monochromatic, how many values, shades of gray, are required? Tapestry artists have had to consider questions of this kind for centuries, taking full account of the viewing distance of the observers. Although the application is different, the same set of problems arise in the context of quantized displays used for target recognition. In the previous section, the conditions under which an individual pixel will be visible was determined. The experiments described below are a first step towards defining the cognitive demands of the observer; the number of pixels required to describe an object and the number of gray shades required.

Three pilot experiments were conducted to determine the sensitivity of operator performance in finding and recognizing targets to variations in a select set of display characteristics. These studies dealt with quantized sensor information. One study used radar imagery and the other electro-optical imagery. The radar study was conducted as part of a different classified project, but the pertinent facts related to sensor display criteria are included in this report. These experiments are described below.

Radar Study

Ground mapping radars are typically used by the operator to find stationary targets or landmarks whose coordinates are known and about which the crew will have been thoroughly briefed. The increasing planned use of digital scan conversion to map the radar video to the display raises the issue of the proper match between the capacity of the radar — its resolution, coverage, dynamic range, and modulation-and the quantization intervals chosen for the scan converter. The effect of digital scan conversion is to spatially map the sensor data to the display by picture elements; pixels. The experimental display resolutions used in these studies are described by the number of pixels per display diameter or by the number of pixels per inch. The independent variables and fixed conditions chosen to the experiment are listed in Table 15.

TABLE 15. RADAR STUDY

INDEPENDENT VARIABLES

SPATIAL QUANTIZATION:	247 PIXELS (34 per inch)
	514 PIXELS (71 per inch)
GREY SCALE QUANTIZATION:	4 GREY SHADES (2 bits)
	8 GREY SHADES (3 bits)
	16 GREY SHADES (4 bits)

FIXED CONDITIONS

Display Size:	7-1/4 inches, square
Ground Coverage:	Constant (value classified)
Imagery:	Synthetic Array Radar
Radar Type:	Side Looking
Display Luminance:	10 fL
Ambient:	1 fL
Display Dynamic Range:	50:1

INDEPENDENT VARIABLES

Response Time

Recognition Error

Imagery. The radar imagery was film records of high quality side-looking radar video. The same target area was mapped at two different radar ground resolutions which allowed the comparison of the effects of sensor resolution as distinct from display resolution. This imagery is classified and to keep the body of this report unclassified, prints of the imagery or data concerning the radar resolutions have been omitted.

Targets. Twelve radar targets were used in the experiment. The targets, target aimpoints, general target locations, and useful cues around the targets are given in Table 16.

Laboratory Equipment. The principal parts of the Hughes simulator used in this study are depicted in Figure 16. In the upper left are shown two sensor simulation devices — a television scanner (TVS) and a cathode ray tube flying spot scanner (FSS). These units scan rear-illuminated

TABLE 16. TARGETS AND BRIEFING CUES

Target Number	Target Type	Target Aimpoint	General Target Location	Useful Cues Around Target
1	3-way Road Junction	Center of Junction	Rural area	Inverted Y shape (⅄) formed by roads leading to junction
2	Earthen Dam	Center of dam separating two bodies of water	Rural area	Shape of shore line
3	Freeway Overpass	Dead center on the overpass	Rural area	X-shape formed by the freeway and crossing road
4	Bridge	Center of bridge	Industrial-residential area	S-shape bend in river below target; horizontal orientation of road crossing river
5	Dirt Trail Junction	Center of Junction	Rural area	X shape formed by roads meeting at junction; contrast differences between one side of junction and the other
6	Corner of Field	Upper left corner of field	Rural area	Contrast difference between field and background; irregular shaped field to upper right of target
7	Stream Junction	Center of stream junction	Rural area	Contrast difference which splits the moor almost directly in half; runs through the steam junction
8	Bend in road	Center of bend in road	Rural area	L-shape of road
9	Junction of road and canal	Center of junction	Rural area	X-shape formed by crossing of road and canal; irregular shaped patch of trees to upper right of target
10	Power Plant	Center of power plant	Industrial-residential area	Shape of the body of water adjoining the power plant
11	Administration Building	Dead center on roof of building	Residential area	Freeway complex forms sideways Y around target area; target located near housing development
12	Building	Center of roof	Rural area	Backwards L-shaped road to left of target

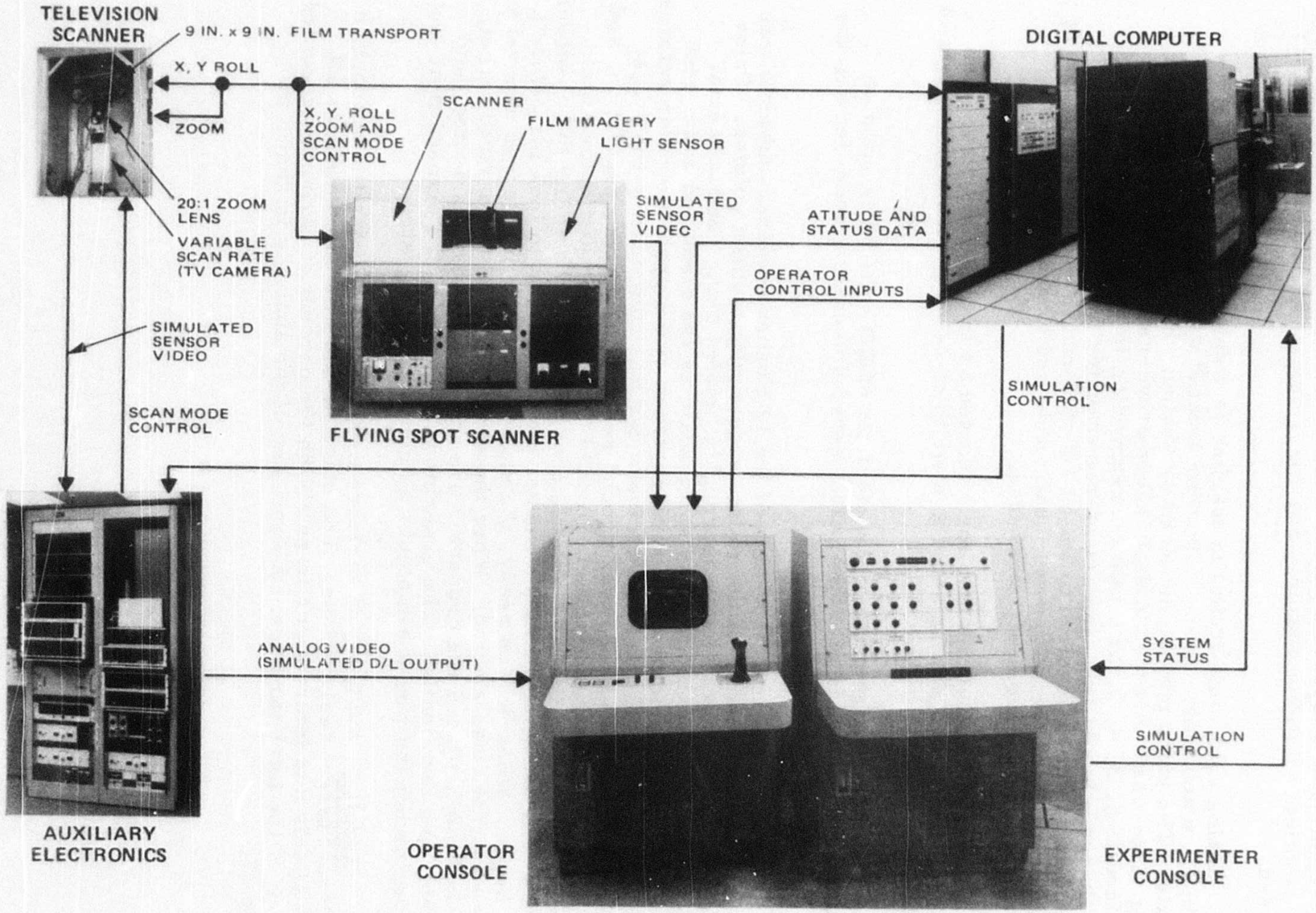


Figure 16. Hughes simulator.

photographic film imagery to produce video data simulating video from an electro-optical or radar sensor. For these studies the television scanner was used.

Analog video data from the scanner is displayed directly on the variable line and frame rate TV monitor located within the Operator's Console. The video may be digitized or analog. For these studies, the analog video was converted to digital format where gray levels were quantized to 2, 3, 4, 5, or 6 bits corresponding to 4, 8, 16, 32, and 64 gray shades. In addition, the brightness transfer function (BTF) may be varied from a linear function to one of 100 different non-linear relationships. For these studies, the BTF was visually selected to provide a pleasing picture and was subsequently measured.

A 14-inch television monitor was used as the video display. The raster on the display was adjusted to a width of 7-1/4 inches and a height of 7-1/4 inches.

When the oblique view characteristic of EO sensors is simulated, closure on the target is provided with a servo driven 20:1 zoom lens on the Television Scanner (TVS).

Operators' Task. The task of the 12 Hughes engineer-subjects was to designate the aimpoint of the radar targets with a small pointer. Prior to each trial, the operator was thoroughly briefed using vertical aerial photographs of approximately the same scale as the displayed radar test imagery. He was also provided with sketches of the probable radar returns and was told the direction at which the radar was illuminating the target area. The combination of radar ground resolution, display resolution, and grey scale quantization was also provided the observer just before each experimental trial. Considerable time was devoted to briefing the observer in order that he might develop a mental picture of what to look for before a trial began. When he was ready, the stationary radar image was uncovered, and a stopwatch was started. When the observer found the desired target, he said "now", placed the crosshair over the target he had selected, and the trial was terminated. The experimenter recorded the elapsed time and whether or not the target aimpoint was correctly designated.

Results. Analyses of variance were computed using the proportion of correct target designations. The statistic Eta was calculated for all main effects and interactions to establish the percent of variance accounted for out of the total variance. A summary of the analysis is shown in Table 17.

TABLE 17. ANALYSIS OF VARIANCE SUMMARY: PROPORTION OF CORRECT TARGET RECOGNITIONS

Source of Variation	DF	SS	MS	ETA
1 Grey Scale Quantization	2	0.00815	0.00498	0.0283
2 Display Spatial Quantization	1	0.00241	0.00241	0.0084
3 Sensor Resolution	1	0.2324	0.23241	0.8063
1 x 2	2	0.02042	0.01921	0.0708
1 x 3	2	0.01482	0.00741	0.0514
2 x 3	1	0.00001	0.00001	0.00003
Residual 1 x 2 x 3	1	0.01002	0.01002	0.0348
Total	11	0.28822		

Gray Shade Quantization. The main effect of gray shade rendition is shown in Figure 17. Cumulative percent probability of correct recognition is plotted as a function of time. As can be seen from the graph, there was little performance difference between the 3- (8 gray levels) and 4-bit (16 gray levels) conditions.

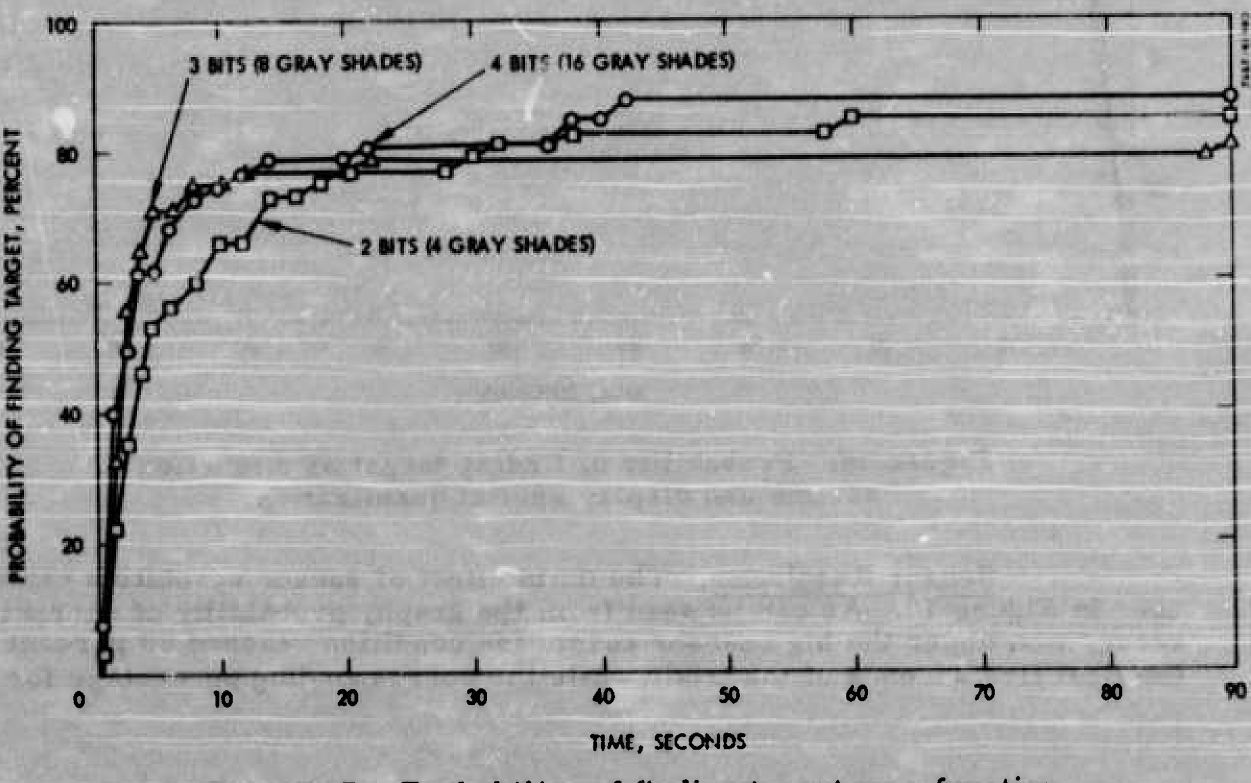


Figure 17. Probability of finding target as a function of time and gray scale quantization.

The 2-bit condition (4 gray levels) was inferior to the 3- and 4-bit conditions in the number of correct recognition responses made during the first few seconds. In terms of final performance (probability of correct target recognition), there was little difference between the 2-, 3-, and 4-bit conditions. The analysis of variance, Table 17, indicates that the main effect of grey shade rendition failed to attain statistical significance.

Spatial Quantization. The main effect of spatial quantization can be seen in Figure 18. As can be seen from the graph there was a slight indication that the 71 pixel quantization fostered higher percentages of correct target recognition between 8 and 20 seconds. Terminal performance, however, appeared almost identical for the two conditions. Analysis of variance of the main effect indicates that this variable failed to attain statistical significance.

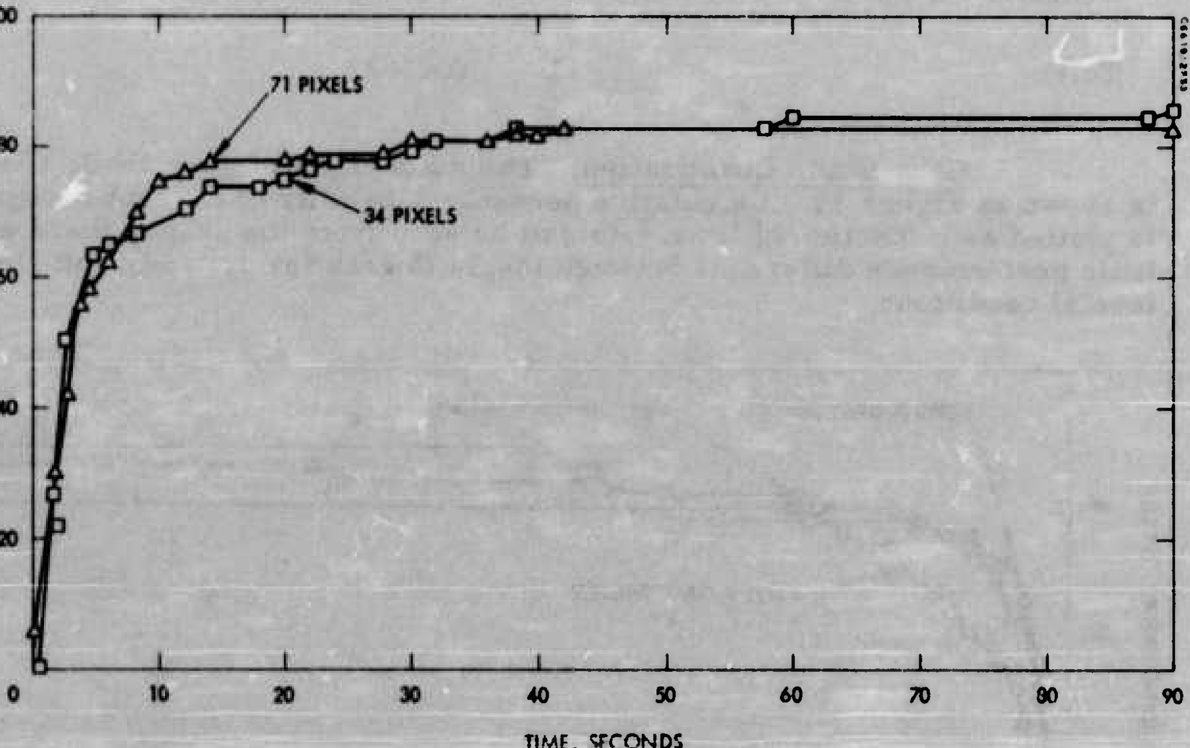


Figure 18. Probability of finding target as a function of time and display spatial quantization.

Sensor Resolution. The main effect of sensor resolution can be seen in Figure 19. As can be seen from the graph, probability of correct recognition under the high sensor resolution condition reached 80 percent after the first five seconds of the trials while the corresponding percentage for

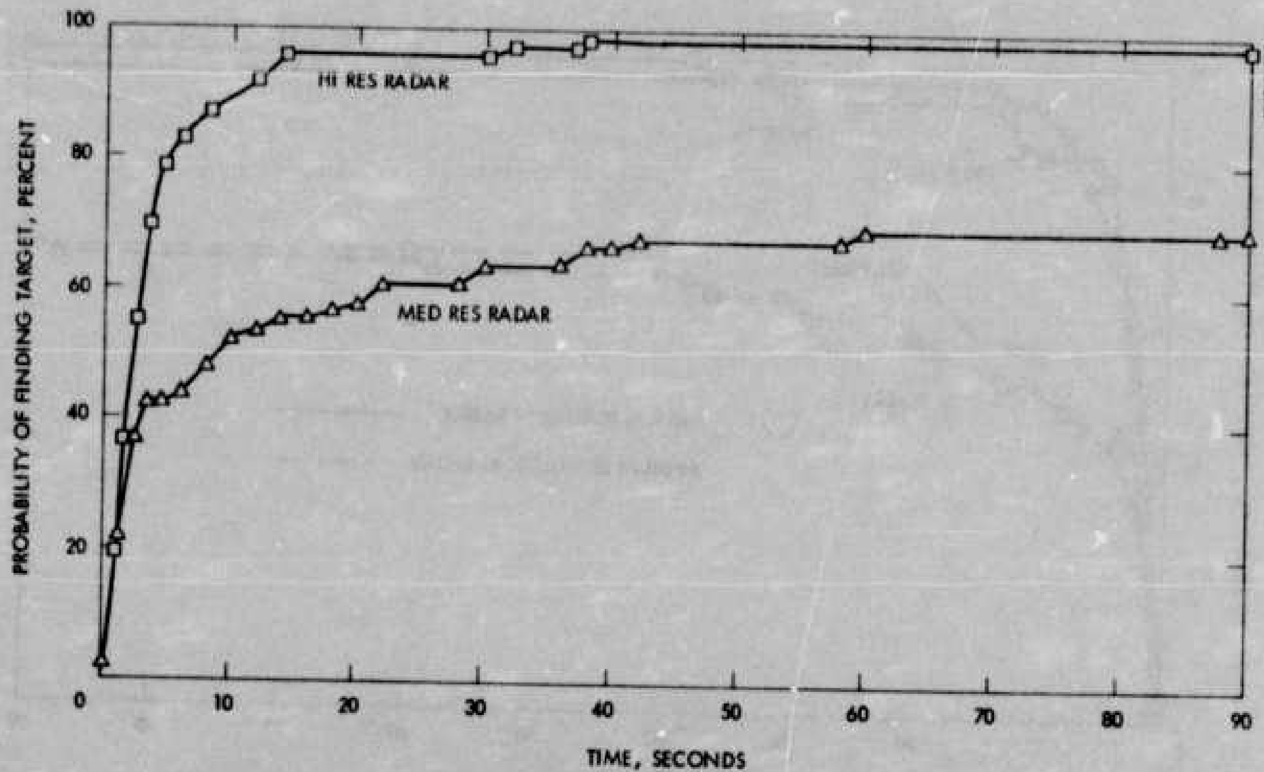


Figure 19. Probability of finding target as a function of time and radar resolution.

the low resolution was only 43 percent. The high sensor resolution retained its superiority over the low resolution through the duration of the trials with terminal performance reaching 98 percent for the high sensor resolution and 70 percent for the low resolution. This difference was satistically significant at the 0.05 level. Calculation of the statistic Eta showed that the effect of sensor resolution accounted for 80 percent of the total experimental variance.

Interactions. None of the interactions was statistically significant Plots of the results of the combination of high and low resolution radar with each of the display quantization levels are shown in Figure 20.

Electro-Optical Studies

Electro-optical ground mapping sensors are not, as is radar, generally restricted to operate against stationary and relatively large targets. For some applications they may, of course, be used to find fixed targets whose location is known a priori, and in this instance the operator's task is similar to that which obtains in radar. That is, the operator will locate the target by use of context and landmark cues as well as the signature of the target. On the other hand, these sensors may also be used to recognize and identify fleeting and non-stationary small tactical targets. For the operator, this is a completely different task than finding a ground target

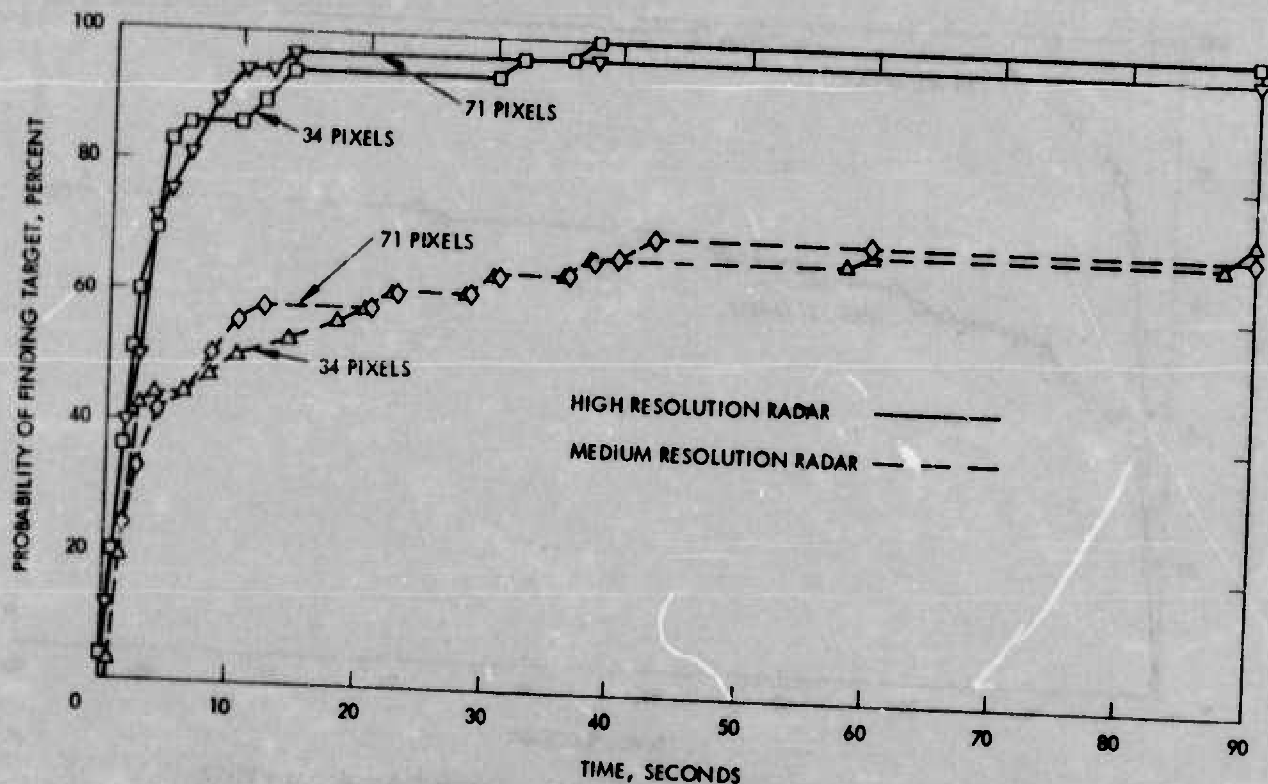


Figure 20. Probability of finding target as a function of time, spatial quantization, and radar resolution.

on a radar display and depends not so much on the gestalt of the contextual information as on his ability to extract a shape signature from the displayed image. This, in turn, may require the discrimination of small modulations within the target. The recognition task, therefore, is expected to be much more sensitive to variations in quantized video.

The EO studies were undertaken to investigate the effects of spatial and intensity quantization interval on operator performance for both kinds of operational tasks, e.g. where the target is relatively large and its position known and where the task is to literally recognize a small tactical target. For the purpose of this report, these tasks have been called "Finding a prebriefed target" and "Recognizing a Vehicle" respectively.

Finding a Prebriefed Target. In these experiments, the task for the operator was to find a stationary target in the image provided by a simulated forward-looking television sensor. The targets included bridges, buildings, and POLs, and the operator was briefed on the particular target he was to find. The experimental variables are listed in Table 18.

TABLE 18. EO STUDY EXPERIMENT PARAMETERS

Independent variables	
Spatial quantization:	34 pixels per inch
	71 pixels per inch
Gray scale:	8 gray shades (3 bits)
	16 gray shades (4 bits)
	32 gray shades (5 bits)
Fixed conditions	
Display size:	7-1/4 inches, square
Luminance:	10 fL
Ambient:	10 fL
Brightness transfer function:	Visually optimized for each image
Imagery:	Oblique aerial photographs
Subjects:	12 Hughes engineers
Dependent variables	
Time to designate target	
Error	

Targets. A represesentative target used in the study is shown in Figure 21. The targets, target aimpoints, general target locations, and useful cues around the targets are given in Table 19.

Imagery. The images from which the targets were selected were taken from medium altitude oblique photography. The originals were copied, cropped, and prepared for use in the simulator. Examples of one target in the various experimental condition are illustrated in Figure 22.

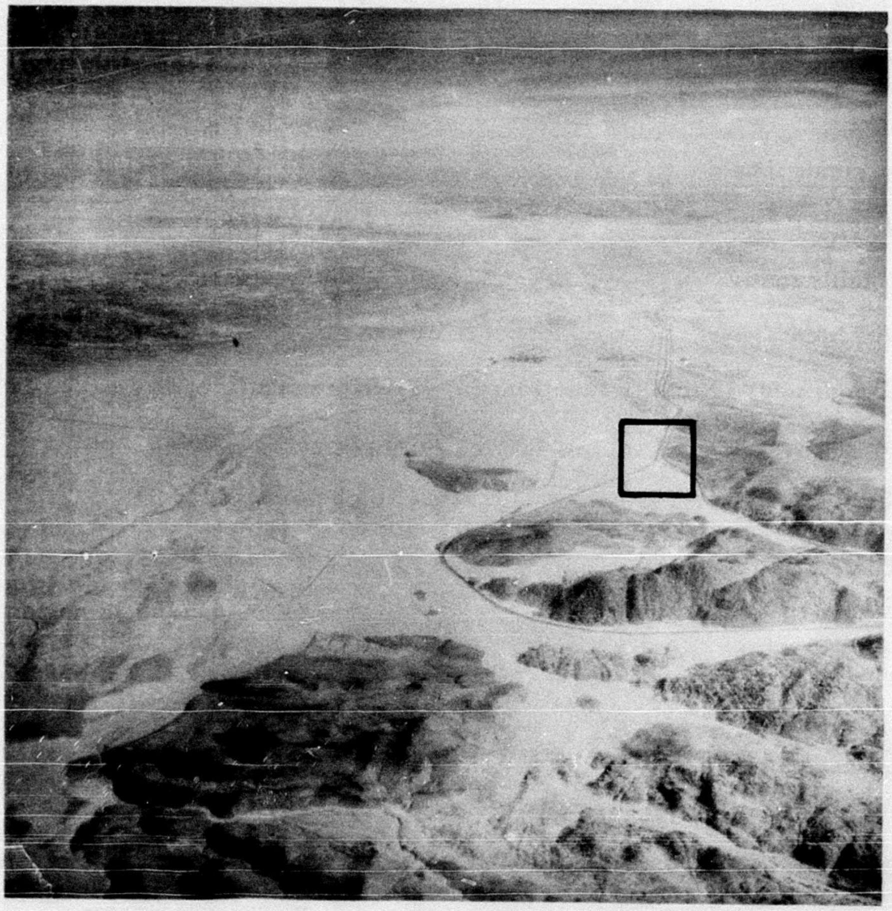


Figure 21. Target No. 4 AF/POL.

TABLE 19. TARGETS AND BRIEFING CUES

Target Number	Target Type	Target Aimpoint	General Target Location	Useful Cues Around Target
1	Railroad Bridge	Center of Bridge	Desert area	Small town to upper left of target; distinct bend in road below target
2	Refinery	POL tank at left side of refinery	Industrial/ rural-residential area	Shape of the town below the target; vertical road running along left side of target
3	Dam	Right hand end of dam	Rural area	Distinct bend in canal below target
4	POL Tanks	Any of the four tanks at the center of the complex	Industrial/ rural-residential area	Airfield to left of target; Pattern formed by open oil tanks (flush with the ground) to the right and left of the target
5	Refinery	Any central tank at the left side of the refinery complex	Industrial/ residential area	Shape of the road complex around the target; Bulge in the river below the target
6	Building	Center of the roof on the building at the lower right corner of the complex	Rural-residential	Housing district to right of the target

Equipment. With some minor changes, equipment was identical to that used for the radar study. To simulate closing on the target, the zoom lens was driven to go through an excursion of 20 to 1 in 60 seconds. Whatever the initial range of the target, the range at the end of 60 seconds was 1/20th of the initial range. The operator was provided with a hand control (see Figure 16) which allowed him control of sensor Az-El line of sight. Using this control, he could place the target under a reticle at the center of the display. A trigger on the hand control stopped the zoom lens and disabled the hand control. A digital timer started at problem initiation and stopped when the observer pulled the trigger. Time and error scores provided the performance data.

Operator's Task. The task of the operator was to find the target as quickly as possible and by use of the hand control, place it under the display reticle and designate by pulling the trigger. Prior to each trial, the observer was briefed on the particular target he was to acquire. Vertical aerial photographs of the target and target area were used for this purpose (see Figure 23). Likely cues in the target scene were pointed out. During training trials, the procedures were demonstrated, and the purpose of the experiment was explained to the subject. Examples of all combinations of experimental conditions were shown. In the experimental runs, each subject was allowed all the time he needed to brief himself before a trial started. When he was ready, he was told the experimental conditions for a trial, the display was uncovered, and the trial initiated. Time to acquire and errors were scored.

Results. The main effects of pixel number and gray scale quantization are plotted in Figures 24 and 25. The plots are cumulative probability as a function of time. There is a clear performance superiority for the 71 pixel display and for the 5 bit gray scale.

Recognizing A Vehicle. In this experiment the task of the operator was literally to recognize a small tactical target. That is, he was required to name the class to which a target belonged. This recognition task, therefore, was expected to be much more sensitive to variations in quantized video. This study was undertaken to study these effects. The experimental variables are listed in Table 20.

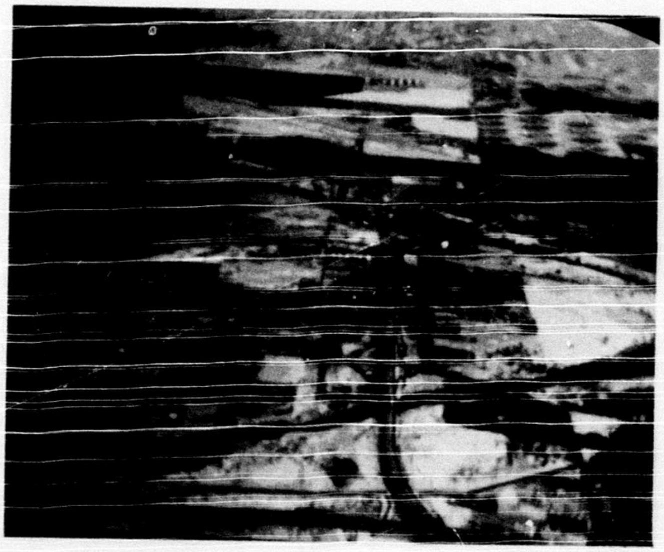
Targets. Six experimental, three dummy, and four training targets were chosen. The targets were: jeep, helicopter, 2-1/2-ton truck, tractor, tracked howitzer, and an armoured personnel carrier (See Figure 26).

Imagery. The images from which the targets were selected were taken from low altitude oblique aerial photography. The originals were copied, cropped, and prepared for mounting in the equipment. Examples of one target in the various experimental conditions are illustrated in Figures 27 through 32.

a. 3 bit

b. 4 bit

34 PIXELS PER INCH



d. 3 bit

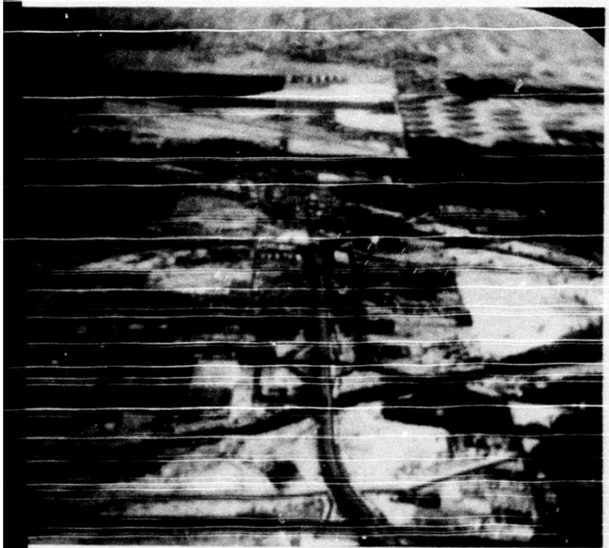
e. 4 bit

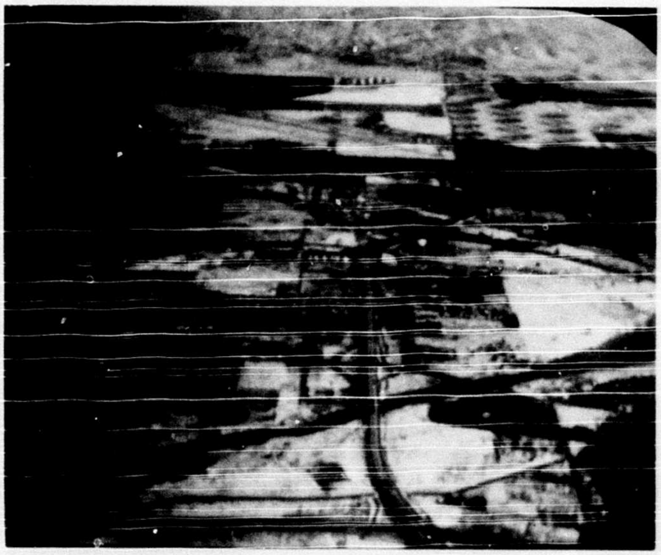
71 PIXELS PER INCH

b. 4 bit

c. 5 bit

34 PIXELS PER INCH





e. 4 bit

f. 5 bit

71 PIXELS PER INCH

Figure 22. Quantized EO image under various experimental conditions. (U)

Figure 23. Example briefing photo used.

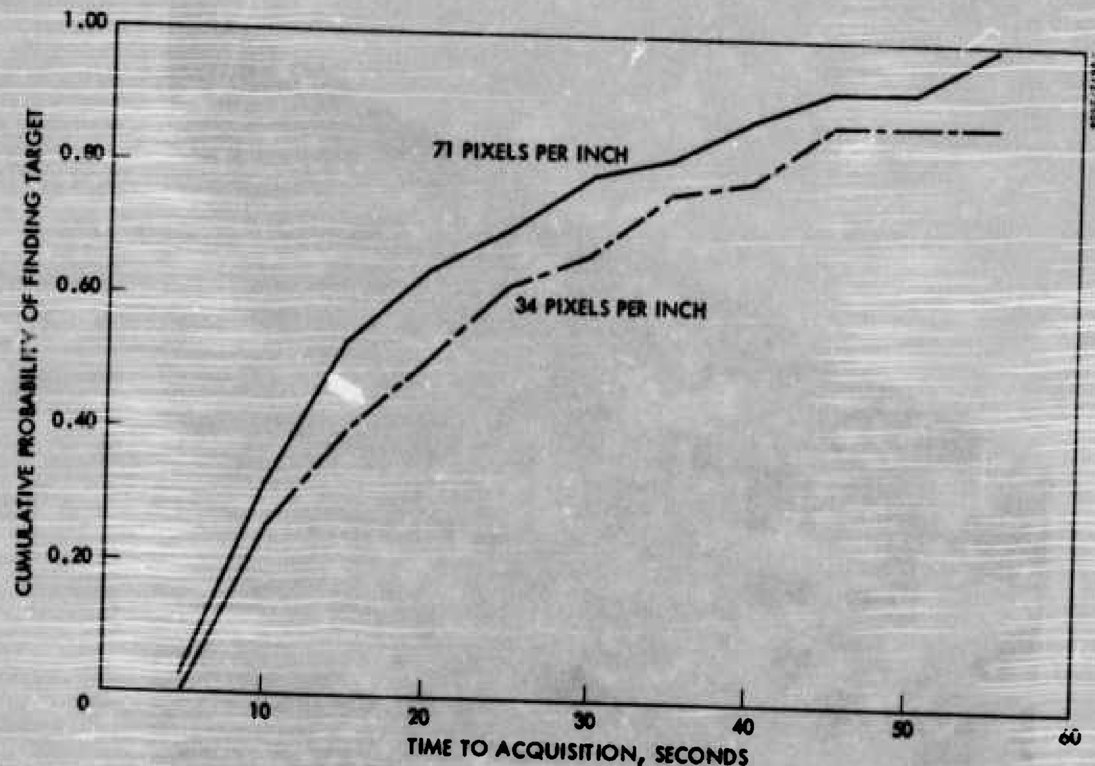


Figure 24. Probability of finding target as a function time and resolution.

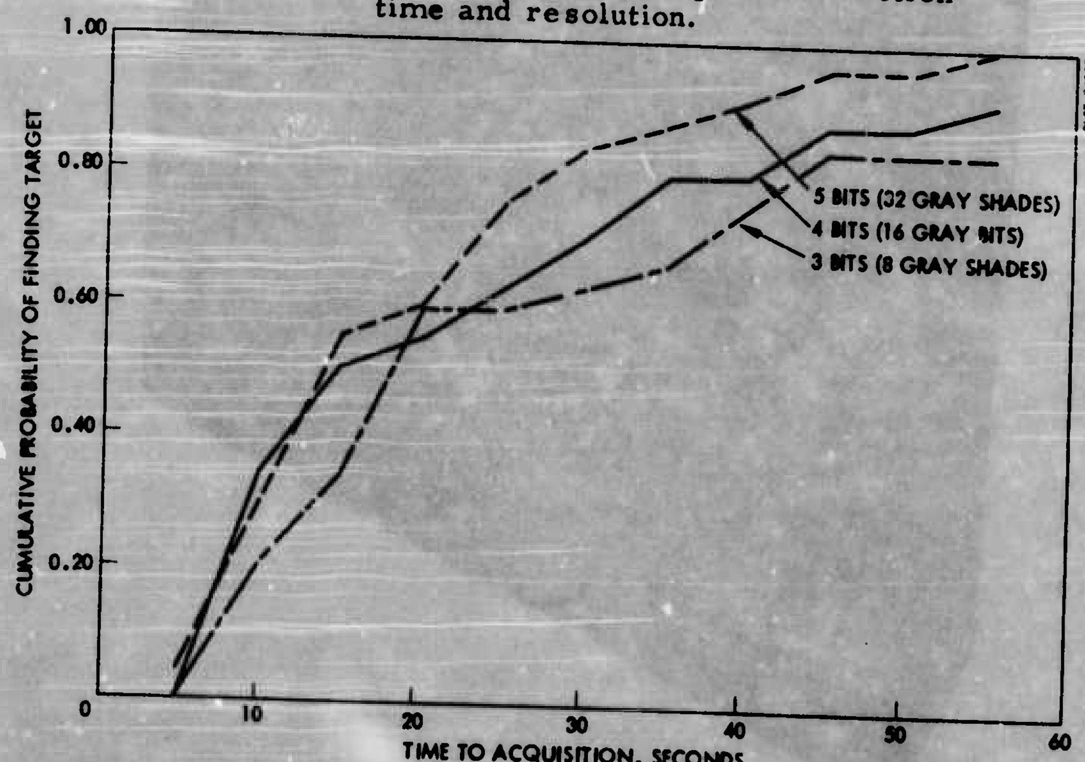


Figure 25. Probability of finding target as a function of time and grey scale quantization.

TABLE 20. ELECTRO-OPTICAL STUDY

INDEPENDENT VARIABLES	
SPATIAL QUANTIZATION:	34 PIXELS per inch
	71 PIXELS per inch
GREY SCALE QUANTIZATION:	8 Grey Shades (3 bits)
	16 Grey Shades (4 bits)
	32 Grey Shades (5 bits)
FIXED CONDITIONS	
Display Size:	7-1/4 inches, square
Luminance:	10 fL
Ambient:	10 fL
Brightness Transfer Function:	Visually optimized for each image
Imagery:	Oblique Aerial Photographs
Subjects:	12 Hughes Engineers
DEPENDENT VARIABLES	
• Target size at recognition	
Definition at recognition	

Equipment. The equipment was identical to that used for the radar study except that a provision for observer controlled manual zoom was used.

Operators' Task. The task of the 12 Hughes engineer-subjects was to correctly name the target at the smallest size (furthest range) possible. Prior to the experimental trials, the observer was shown photographs of the six possible targets. These photographs were pasted on a board and were available for his inspection all the time. The object of the experiment was explained to the observer, and four training trials were conducted to familiarize him with his task. In each trial, the subject started with the image at its smallest magnification. The target he had to identify was circled, and although the target could be seen at the smallest magnification, it could only be seen as a speck or small blob. By turning a potentiometer, the observer gradually

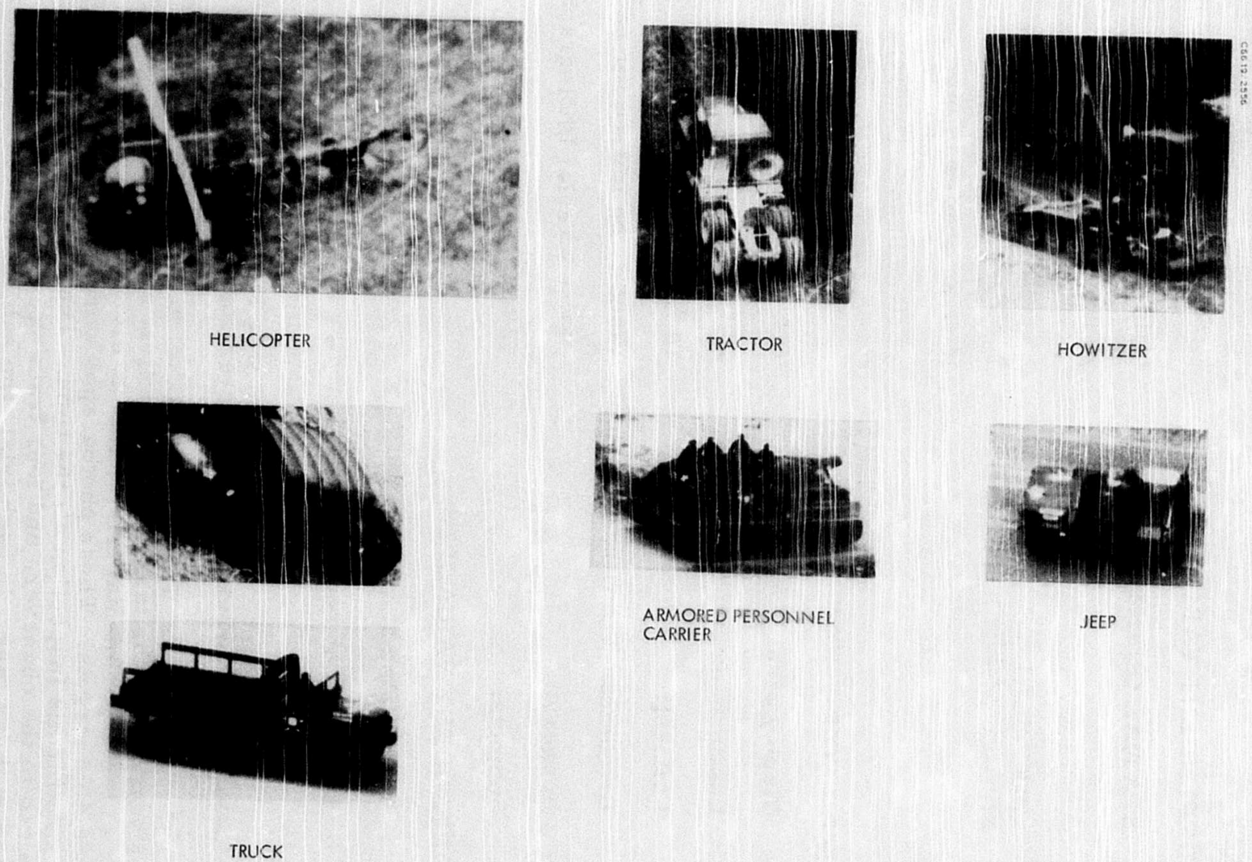


Figure 26. Targets used in experiment.

Figure 27. Tractor: 34 pixels, 8 gray shades (3 bits).

Figure 28. Tractor: 34 pixels, 16 gray shades (4 bits).

Figure 29. Tractor: 34 pixels, 32 gray shades (5 bits).

Figure 30. Tractor: 71 pixels, 8 gray shades (3 bits).

Figure 31. Tractor: 71 pixels 16 gray shades (4 bits).

Figure 32. Tractor: 71 pixels, 32 gray shades (5 bits).

increased the size of the image. His task was to increase the image size until he was reasonably certain about what the target was. Each time the observer made a response, it was recorded, and the size of the image was measured. The observer continued magnifying the image and correcting his original response, if necessary, until he reached the maximum magnification. The point at which the first correct response was made provided the basic data for the results.

Results. The size of the target at correct recognition was the primary dependent variable. For each trial, the longest dimension of the target at correct recognition was recorded. In addition the number of pixels across the target was calculated for each trial. Means and standard deviations for size and for pixels per target (definition) were calculated for each condition.

The results are illustrated in Figures 33 through 36 and tabulated in Table 21. Gray scale quantization yielded poor performance for 3 bits (8 shades) but there was very little difference between 4 and 5 bits. This was true overall and within each of the spatial quantization levels. The level of spatial quantization affected operator performance markedly. Averaged across grey scale quantizations, the targets were recognized at 0.44 inch for the 71 pixel display and at 0.63 inch for the 34 pixel display. On the other hand, fewer pixels were required for recognition at the coarse spatial quantization than at the fine quantization; about 21 pixels for coarse to 31 for fine. This

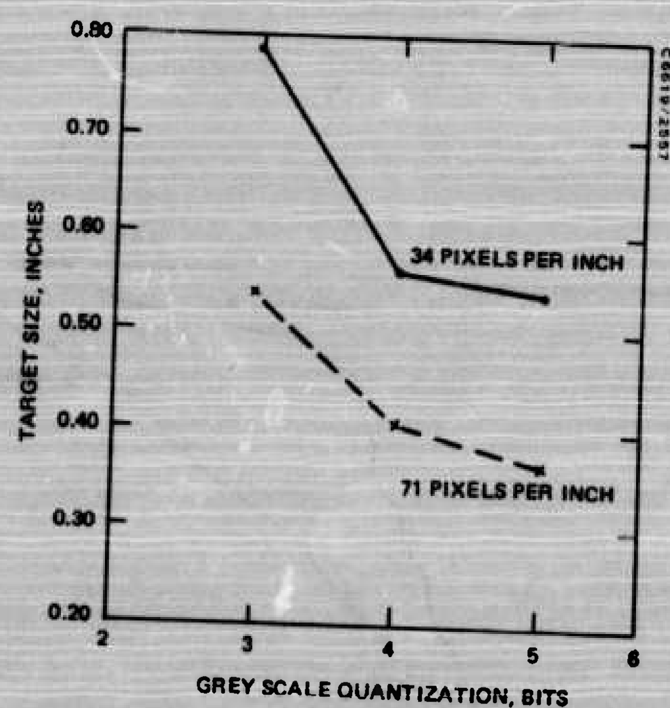


Figure 33. Size required for target recognition in the EO study.

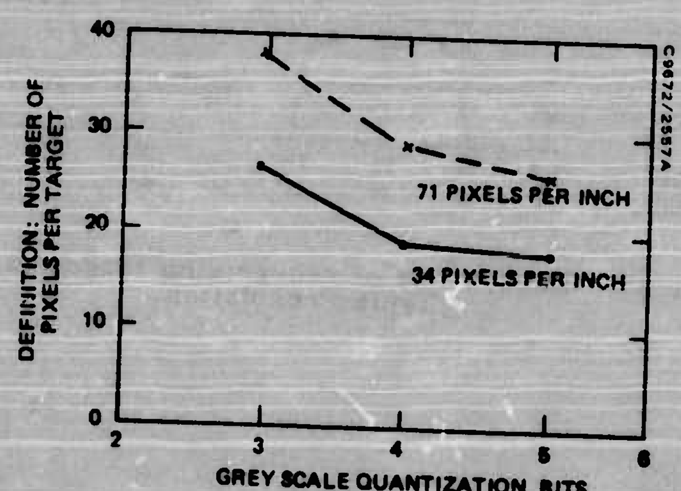


Figure 34. Definition required for target recognition in EO study.

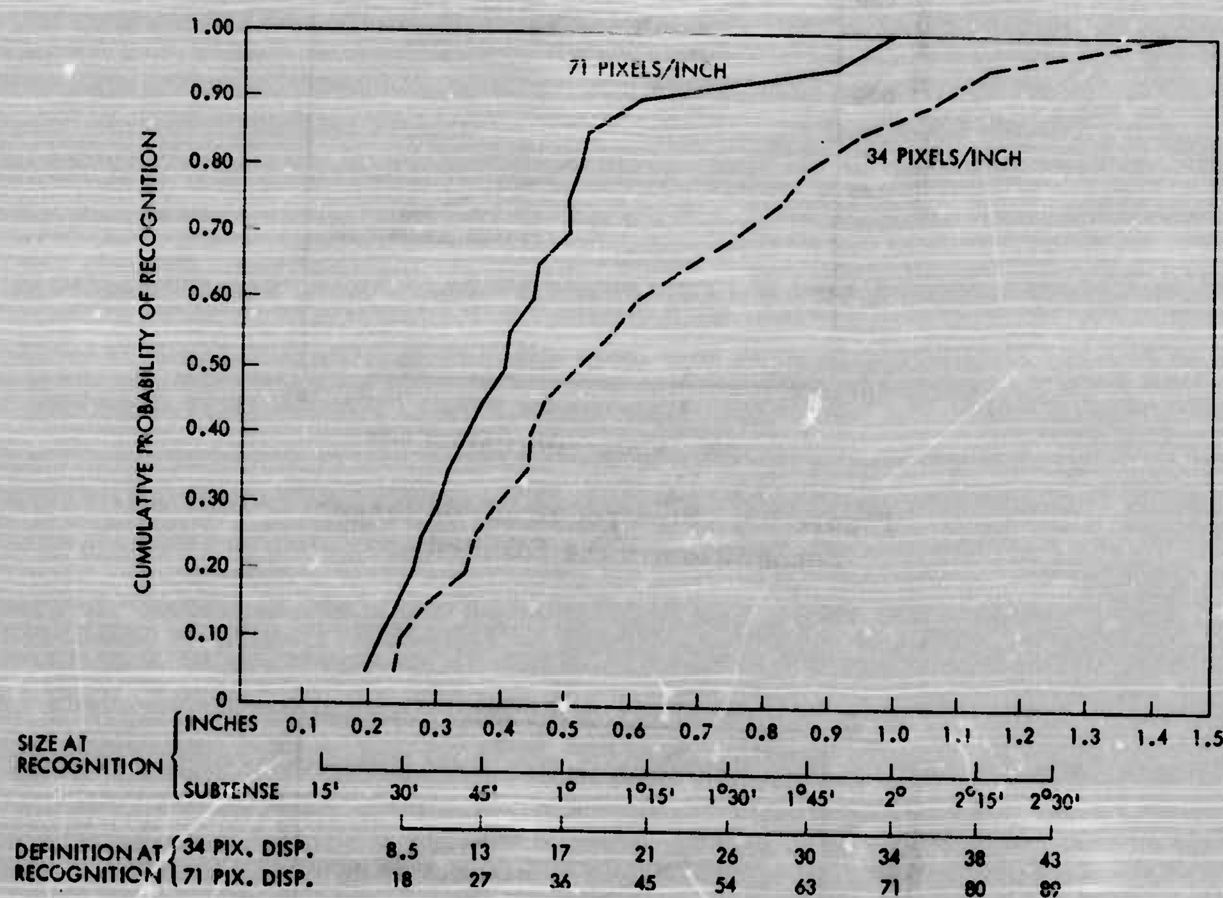


Figure 35. Probability of recognizing target as function of display resolution.

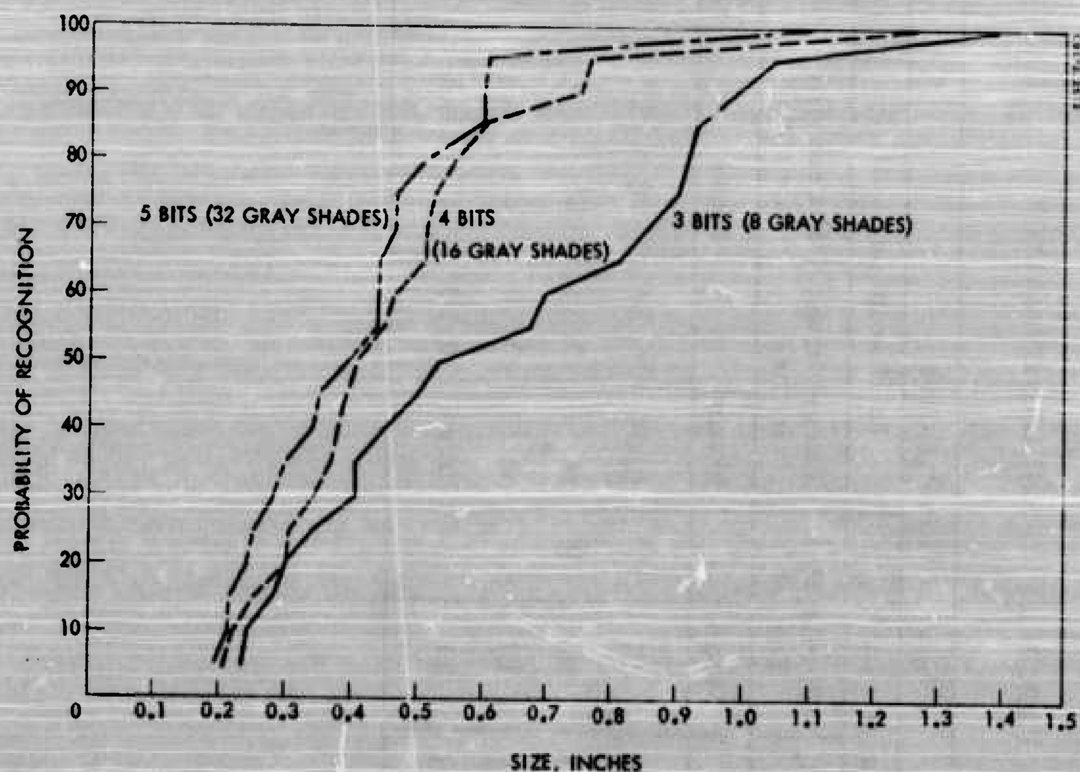


Figure 36. Probability of recognizing target as a function of gray level bits.

TABLE 21. RESULTS SUMMARY

Grey Scale Quantization	Spatial Quantization											
	34 Pixels per Inch				71 Pixels per Inch							
	Target Size, inches		Pixels Per Target		Target Size, inches		Pixels Per Target		Target Size, inches		Pixels Per Target	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
3 bits (8 shades)	0.78	0.33	27	11	0.54	0.24	38	17	0.66	0.32	32	16
4 bits (16 shades	0.56	0.27	19	9	0.41	0.11	29	8	0.48	0.22	24	10
5 bits (32 shades)	0.54	0.27	18	9	0.37	0.16	26	11	0.46	0.24	22	11
	0.63	0.31	21	11	0.44	0.19	31	14				

general relationship holds across gray scale quantization levels. Analyses of variance were calculated for both target size and definition (number of pixels per target). Eta's were also calculated for each variable. Eta provides an estimate of the percent of variance accounted for by each variable. The results of these analyses are shown in Tables 23 and 24.

These data may be converted to relative performance scores by normalizing to percentages. Using the size criterion, the best performance was obtained with 71 pixels and 32 gray shades. If this performance is called 100 percent, the relative performance of the other conditions is as shown in Table 25. Using the definition criterion, the best performance was obtained with 34 pixels and 32 gray shades. If this performance is called 100 percent, the relative performance of the other conditions is as shown in Table 26.

Discussion

The results of these two experiments, taken together, demonstrate the dependence of display design criteria on the task of the operator. The results from the radar study indicate that when the operator is thoroughly briefed, is looking for a target whose coordinates are known, and uses landmarks and contextual cues to find the target, the resolution and gray scale rendition of the display can vary over a wide range without having a major effect on radar target recognition performance. The critical variable is, of course, the characteristics of the sensor; the high resolution radar "sees" a different world than the medium resolution radar and the fact that those different worlds may be mapped to the display at different display resolutions makes little difference. A small difference occurs when the gray scale quantization falls below 3 bits, therefore 3 bit video is the recommended radar video quantization for the MMSDS.

Performance in finding a prebriefed target using an EO sensor is somewhat more sensitive to display quantization variations. Performance was better with the higher resolution and higher number of gray scales. It is interesting that the effects of these variables are different in the radar case and the electro-optical case in spite of the fact that the task of the operator — finding a prebriefed target — is nominally the same.

In the EO sensor case, the quantization intervals provided the limiting aperatures for the system. A change in the spatial resolution — the pixel count — changed not only the display but the ground resolution. Performance, therefore, can be expected to be more sensitive to quantization variations.

A second order effect is hypothesized to occur because of formatting. The display of the radar data is in exactly the same coordinate system as the reference aids that the operator used to brief himself. The reference aids (vertical photographs) and the radar map are both plan-position and the pattern of landmarks and other cues are congruent. This makes it relatively easy to find a target on the radar map given that its relation to landmarks is known from the briefing photograph. With the forward looking EO sensor, the display is essentially a perspective transformation of the ground, the world is considerably foreshortened, and there is no direct congruence

TABLE 22. ANALYSIS OF VARIANCE SUMMARY: TARGET SIZE AT RECOGNITION

Source of Variation	Degrees Freedom	Sum Squares	Mean Square	F-Ratio	Change Probability	ETA
1 Spatial Quantization	1	0.6463	0.6463	18.42	0.001	11.69
2 Grey Shade Quantization	2 5	0.5985	0.2992	8.53	0.001	10.83
3 Targets	5	1.2009	0.2401	6.84	0.001	21.72
1 x 2	2	0.0295	0.0147	0.42		0.53
1 x 3	5	0.7811	0.1562	4.45	0.01	14.13
2 x 3	10	0.5030	0.0503	1.43		9.10
1 x 2 x 3	10	0.5050	0.0505	1.44		9.14
Replications	36	1.2633	0.0350			22.85
Totals	71	5.5281				

TABLE 23. ANALYSIS OF VARIANCE SUMMARY: DEFINITION AT RECOGNITION (U)

Source of Variation	DF	SS	MS	F	P	ETA
1 Spatial Quantization	1	1708.8	1708.8	23.81	0.001	13.59
2 Grey Shade Quantization	2	1413.2	706.6	9.85	0.001	11.24
3 Targets	5	2335.5	471.1	6.56	0.001	18.73
1 x 2	2	39.6	19.8	0.28		0.31
1 x 3	5	1342.2	268.4	3.74	0.01	10.67
2 x 3	10	1563.9	156.3	2.18	0.05	12.44
1 x 2 x 3	10	1568.8	156.8	2.19	0.05	12.47
Replications	36	2583.8	71.7			20.55
Totals	71	12576.1				

TABLE 24. RELATIVE PERFORMANCE USING SIZE CRITERION

Intensity Quantization	Spatial Quantization	
	34 Pixels Per Inch	71 Pixels Per Inch
3 bits (8 shades)	47%	68%
4 bits (16 shades)	66%	90%
5 bits (32 shades)	68%	100%

TABLE 25. RELATIVE PERFORMANCE USING DEFINITION CRITERION

Intensity Quantization	Spatial Quantization	
	34 Pixels Per Inch	71 Pixels Per Inch
3 bits (8 shades)	67%	47%
4 bits (16 shades)	95%	62%
5 bits (32 shades)	100%	69%

between the forward-looking sensor image and the vertical photograph on which the operator was briefed. The system therefore is more sensitive to the granularity of the mapped information — the pixel count and the grey scale quantization.

Performance is even more sensitive to quantization granularity when the operator must recognize a target by its silhouette and small modulation differences within the target. Recognition performance of small electro-optical sensor targets as a function of the number of quantized grey levels takes a sharp dip when the grey levels fall below 16 (4 bits). The loss in performance as a function of grey levels is portrayed in Figure 37.

For this kind of task, if the size and scale factor of the display is fixed, it is clear that the higher resolution display (71 pixels per inch) yields better performance; recognition occurred when the target was 0.44 inch in size for the high resolution as compared to 0.63 inch size for the low resolution. This implies that a target will be recognized at greater range with the high resolution display.

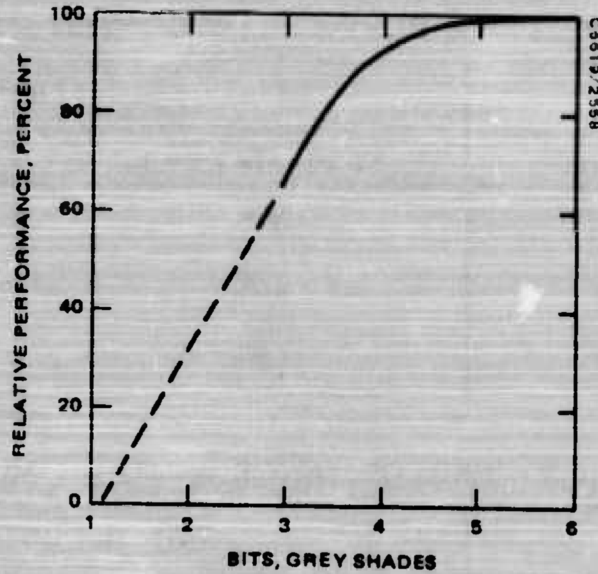


Figure 37. Relative recognition performance as a function of gray scale quantization.

If on the other hand, there are no constraints on the display size, better performance will be obtained with the coarse resolution display (34 pixels per inch). The data show that 22 pixels across the target are required when the coarse resolution is used, but 31 pixels are required for the high resolution display. In these circumstances, the target will be recognized at longer range with the coarse resolution display.

The most convenient hypothesis to account for these paradoxical data is one that involves both the MSF of the eye and the cognitive demand, i.e., the amount of information needed to reach a conclusion about the object being viewed. With the high resolution display viewed in the experimental conditions described, each pixel subtended 2 arc minutes and with the coarse resolution 4 arc minutes. This corresponds to 15 and 8 cycles per degree respectively. Examination of the psychophysical MSF data show that the modulation required for a 15 cycle (30 pixel) image is considerably greater than that for the 8 cycle (16 pixel) image. This implies that the small modulations between individual pixels can be more easily discriminated visually when the pixel size conforms to the spatial frequency where the luminance threshold is lowest, i.e., 16 pixels per degree. The coarse resolution display satisfies that visual condition, and the limit to recognition performance is therefore contingent on the amount of information provided the operator. In these experiments, the recognition task of the operator required about 22 pixels (10 line pairs) across the major axis of the target. Targets were not recognized with the high resolution display (30 pixel/degree) when the same number of pixels were laid across the target. This is probably because a spatial frequency of 30 pixels per degree requires more modulation for discrimination than does 15 pixels, and the required modulation did not exist in the target images.

These preliminary results suggest a constant product rule first proposed by Erickson (Ref. 7) that within limits, may be used in display design tradeoffs. This rule says that equivalent performance will be achieved when the product of target size and definition is constant. Target size is expressed in minutes of arc subtended at the observer's eye and definition as the number of pixels per target major axis. For the case in hand, the constant product for high probability of recognition and at least 32 gray shades equals 1430. Using the data from this pilot study and some corollary assumptions, a plot of various probabilities of recognition as a function of target subtense, pixels per target, and gray scale quantization has been constructed and is shown in Figure 38. The circles indicate data points and the dotted lines extrapolations. These curves should be considered as working hypotheses that require further empirical confirmation.

2.3.3 Summary

The results of the analyses and experiments related to operator requirements can be summarized in tabular form to provide boundary values of design characteristics based on operator performance (See Table 26). The preceding text explains more fully the variations in performance that accompany design changes and supplies the rationale for the tabulated values. From these results a display raster density of approximately 100 lines per inch is recommended with a maximum quantized display density of 100 pixels/inch. The CRT should use a green phosphor and be refreshed at a 60 Hz rate. Digital radar video should be displayed with a 3 bit intensity quantization and at least 4 bits is required for digitized Electro-Optical Sensors.

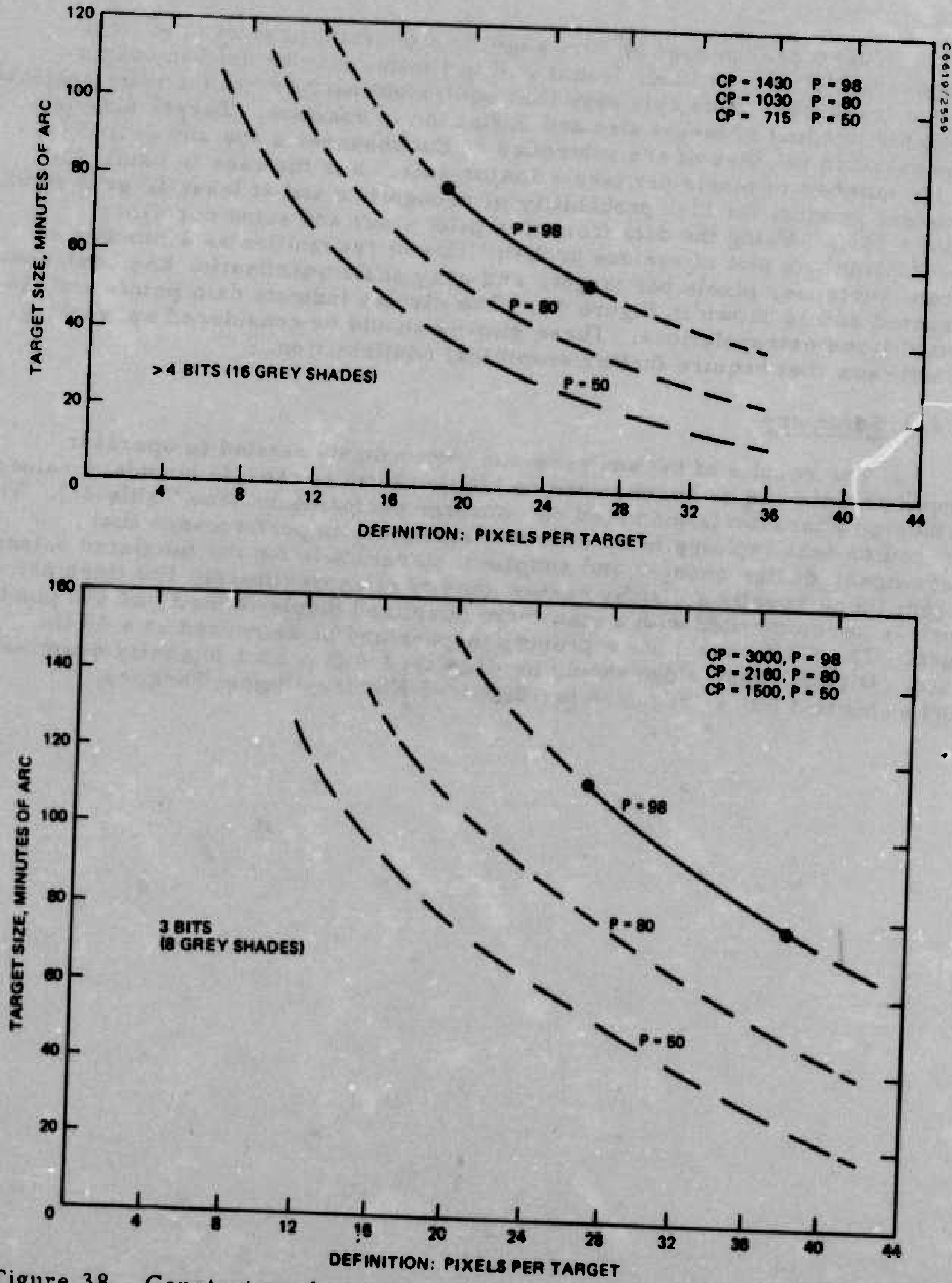


Figure 38. Constant product criteria indicating probability of recognition as a function of target size, definition, and gray scale quantization.

TABLE 26. EXPERIMENTAL STUDY RESULTS

Display Characteristic	Ground Map, Radar Quantized Display	Electro-Optical Sensor		Criteria for Design Recommendation
		Analog Display	Quantized Display	
Active Raster Lines	≥100 per Inch	≥100 per Inch	≥100 per Inch	• Flat Field • Based on Visual MSF Limit
Pixels per Inch	>50, <100	N.A.	>50, <100	• Visual MSF
Dynamic Range	>10:1, <1000:1	>100:1, <1000:1	>100:1, <1000:1	• Gray Shade Requirement • Visual Dynamic Range
Gray Scale Quantization	≥3 Bits (8 Shades)	N.A.	≥4 Bits (16 Shades)	• Experimental Data
Average Effective Luminance, fL*	>0.05 x Adaptation Luminance (Day); ≥0.1 fL (Night)	>0.05 x Adaptation Luminance (Day); ≥0.1 fL (Night)	>0.05 x Adaptation Luminance (Day); ≥0.1 fL (Night)	• Visual Adaptation Window
Phosphor Color	Green	Green	Green	Visual Adaptation Window
Refresh Rate	60 Hz	60 Hz	60 Hz	Visual CPFF

*The Luminance The Operator Sees.

3.0 DESIGN PERFORMANCE CRITERIA

3.1 Major Design Parameters and Summary of System Requirements

The sensor characteristics and human operator requirements have been discussed in the preceding section. The purpose of this section is to define the parameters which must be specified in the design of the modular multisensor display system and to derive quantitative evaluation criteria to measure the system performance as a function of these parameters. Emphasis in this section is placed on establishing design parameter values which do not degrade the sensor capability. Where necessary, the practical limitations imposed by the operator characteristics or installation limitations are used to modify the specified parameter values. A summary of the major design parameters and the criteria for selecting mechanization values is given in Table 27.

The main elements of a digital scan converter display system are shown in Figure 39. The key design parameters which must be specified for each element are listed below each functional block. A specific display system design is bounded on one end by the sensor characteristics and on the other end by the operator characteristics and mission performance requirements or task requirements, i.e., detect airborne targets or recognize a specific type of ground vehicle. The operator characteristics and the task requirements have the major influence on the design requirements for the display, such as size, resolution, brightness and contrast. The resolution requirement at the display determines the resolution requirements for the scan converter main memory, while the brightness and contrast requirements determine the dynamic range, gamma, and image enhancement requirements in the input and output processing.

The following paragraphs provide a detailed discussion of the design evaluation criteria which can be used to determine the requirements for the display system mechanization or to evaluate the performance of a particular system mechanization. The application of this design criteria should in most cases result in a system design that does not degrade the sensor performance. However, there is one area of design, which is difficult to specify quantitatively with the current data available, and this is the area of the video intensity transfer function. The selection of the optimum number of quantization bits, 3, 4, 5, or 6 bits; the shape of the transfer function, linear, logarithmic, lin-log or some other non-linear function; the effects of contrast enhancement video processing; and the actual operator performance sensitivity to these functions is not completely understood at this time. Some preliminary data on operator performance as a function of gray shade quantization was included in the preceding section on human operator requirements, but this data represents only a limited sample and cannot be generalized to apply to all situations. Continuing efforts should be applied to develop more data in this area.

The design mechanization criteria developed in this analysis was applied to the sensor list established in Section 2 and the resultant display system mechanization parameters for each sensor system is tabulated in Table 28.

TABLE 27. SUMMARY OF DESIGN PARAMETERS

Parameter	Mechanization Criteria	Comment
$N_{A/D}$, Number of A/D Converter Bits	$N_{A/D} = \frac{\text{Sensor video dynamic range (db)}}{6 \text{ (db)}}$	3-4 bits for radar 4-6 bits for electro-optical
$f_{A/D}$, A/D sampling frequency	Radar: $f_{A/D} \geq \frac{1}{\tau}$ FLIR or TV: $f_{A/D} \geq 2f_{max}$ (Nyquist criteria)	τ = radar pulse width f_{max} = highest video frequency of interest $f_{A/D}$ is normally selected to provide a binary number of samples in a radar range sweep, i.e. 512 samples in 20 miles ($f_{A/D} = \frac{512}{20 \times 12.38}$ = 2.1 MHz) $f_{A/D}$ may be variable within one range sweep to provide ground range sweep correction

Table 27. (Continued)

Parameter	Mechanization Criteria	Comment
R_I, Number of integrator range bins	$R_I = \frac{12.38 \times \text{Range scale (NM)}}{\tau\ (\mu sec)}$	If R_I is greater than the display range resolution, it may be reduced by a range bin collapsing technique such as averaging or peak detection
β, Integrator feedback constant	$\beta = e^{-\frac{1.17}{M}}$	M = number of PRF's in a 3db antenna beamwidth M: 1-3, 2-7.5, 3-16, 7.5-30, 16-80 β: 1/2, 3/4, 7/8, 15/16, 31/32
$N_{A/D} + K$, Total number of accumulator bits carried in integrator	$K = \log_2 \frac{1}{1-\beta}$	β: 1/2, 3/4, 7/8, 15/16, 31/32 K: 1, 2, 3, 4, 5

M	β
1-3	1/2
2-7.5	3/4
3-16	7/8
7.5-30	15/16
16-80	31/32

β	K
1/2	1
3/4	2
7/8	3
15/16	4
31/32	5

Table 27. (Continued)

Parameter	Mechanization Criteria	Comment
L, Number of gray shade bits stored in main memory	Linear truncation: $L = \log_2 10^{DR/20}$ Logarithmic truncation: $L = \log_2 \left[2 \log_2 10^{DR/20} \right]$	DR = output dynamic range in db DR | L, linear | L, log 6 | 1 | 1 12 | 2 | 2 24 | 4 | 3 48 | 8 | 4
n, number of vertical samples stored	Radar: $n = R_I$ FLIR: n = number of detectors in vertical field of view TV: n = number of scan lines	n is normally picked to match the number of display raster lines in a total frame or in a field and is usually picked to be a binary number or multiple thereof TV raster display | n 525 | 256 or 512 875 | 384 or 768 1023 | 512 or 1024
m, number of horizontal samples stored	Radar B-Scan: $m \geq \frac{2S}{\Gamma}$	S = total scan width in degrees

Table 27. (Continued)

Parameter	Mechanization Criteria	Comment
	Radar PPI: $m \geq \frac{4S}{\Gamma}$ FLIR or TV: $m = f_{A/D} T_a$	Γ = 3db antenna beam-width PPI requirement assumes a TV raster output where m is the total number of samples across the width of the display T_a = active display line time m is normally picked to be a binary number or multiple thereof, i.e. 128, 256, 384, 512, etc.
Display Formats	Depends on sensors, normal formats are: Radar sector PPI B-scan E-scan line-scan strip map Infrared A-scan C-scan TV raster Television TV raster	Formats required affect the memory addressing and timing and control logic

Table 27 (Concluded)

Parameter	Mechanization Criteria	Comment
$f_{D/A}$, Output D/A converter rate	$f_{D/A} = \frac{m}{T_a}$	m = number of horizontal elements T_a = display active line time
g, Output video intensity transfer function	Match gamma of display to provide a $\sqrt{2}$ brightness increase for each video level quantization	Provides 2^L gray-shades on display (gray shade = $\sqrt{2}$ brightness difference)
ω_f, Output video rolloff filter	Matched band limiting filter with aperture correction for $\frac{\sin x}{x}$ rolloff, band limited at output video frequency ω_o >30db/octave rolloff	$\omega_o = \frac{m}{2T_a}$
$N_{D/A}$, Number of D/A Converter Bits	With Analog Gamma Shaper $N_{D/A}$ = L (number of stored memory bits) With Digital Gamma Shaper $N_{D/A}$ = L + required number to provide gamma shaping transfer function	Since CRT is limited to ~100 to 1 dynamic range $N_{D/A}$ max ≈7 bits
2σ, CRT Spot Size	Provide shrinking raster flat field ∴ 2σ = Line Spacing	At 100 lines/inch, 2σ = 10 mil

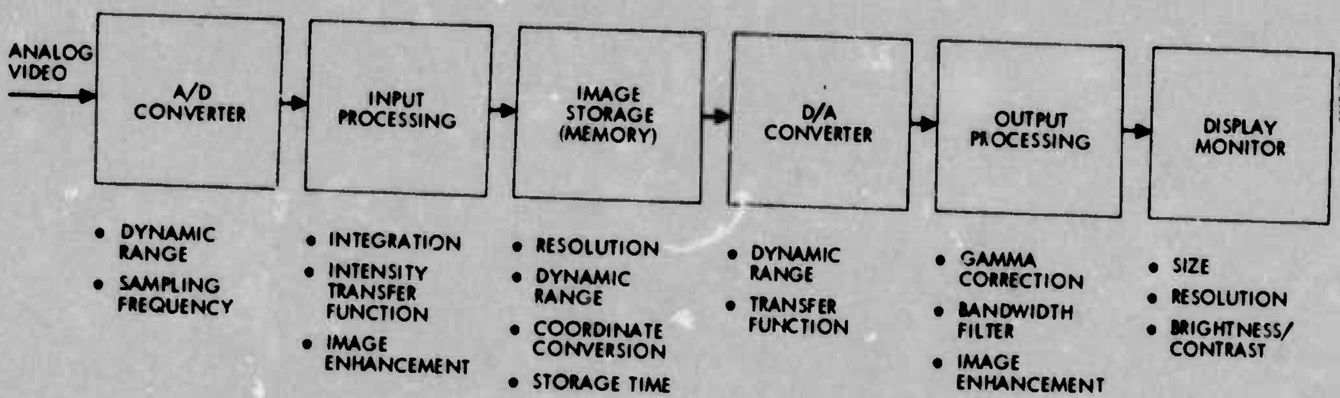


Figure 39. Major functional elements of the digital scan converter display system.

3.2 Analog to Digital Conversion

The A/D converter consists functionally of two components: a boxcar sampler and a digital quantizer. These are shown schematically in Figure 40. The boxcar sampler converts the analog signal to a train of pulses of duration τ, and the quantizer converts the continuous range of pulse amplitudes to a set of discrete levels. The net effect of the A/D converter is to change a signal continuous both in time and amplitude into a discrete signal in both dimensions. Both elements contribute to image noise by the act of quantization and therefore decrease system signal to noise ratio.

The major noise source in a digital display system is the A/D converter. The A/D converter sampling rate also determines the modulation response of the display system assuming the memory and display have sufficient memory capacity and resolution to store and reproduce all of the samples taken by the A/D. In this section, the effect of sampling and quantization on system MTF, dynamic range, and signal-to-noise ratio are discussed.

3.2.1 Sampling Rate

Sampled display systems should accurately reproduce the highest frequencies of interest in the sensor video for each display dimension while introducing a minimum of aliasing. The "highest frequency of interest" is first established for the sensor in terms of sensor parameters. This frequency represents the resolution limit of the sensor (f_o) and is defined at a point where increasing the frequency yields little meaningful sensor information. The sensor video is then assumed to be effectively bandlimited at f_o, and the Nyquist sampling criterion of at least two samples per cycle at the bandlimiting spatial frequency f_o is applied to derive the required number of samples.

Parameter	F-4C AN/APQ -100	F-4D AN/APQ -109	F-4E AN/APQ -120	F-106A, B MA-1 AN/APQ-25	A-7D AN/APQ -126	Air... F-111A Attack Rdr AN/APQ-113	F-111A TF Rdr AN/APQ-110	FB-111 Attack AN/APQ-114	FB-111 AN...
Display Formats	B-Scan PPI B-Scan Exp	B-Scan PPI B-Scan Exp	B-Scan PPI B-Scan Exp	B-Scan	PPI PPI-Exp TC-PPI E^2-Scan	B-Scan PPI PPI-Exp	PPI TC-PPI E^2-Scan	B-Scan PPI PPI-Exp	P... T... E...
Special Requirements					Gnd Rng Swp	Gnd Rng Swp		Gnd Rng Swp	
Number of Displays	2	2	2	1	1	1	1	1	
Display Size (in.)	4	4	4	4	4	7	4	7	
$N_{A/D}$, Number of Quantization Bits	4	4	4	4	4	4	2	4	
$f_{A/D}$, Maximum Sampling Freq (MHz)	2.5	2.5	2.5	4.0	5.0*	2.5	5.0*	2.5	
R_1, Maximum No. of Range bins	1525	1525	1525	1038	976	915	915	915	
M, Number of PRF's in 3 db beamwidths	16-50	8-50	9-31	11-66	13-130	7-80		7-80	
β, Integrator Feedback Constant	31/32	7/8, 31/32	15/16	31/32	31/32	7/8, 31/32		7/8, 31/32	
Total accumulator bits in integrator	9	9	8	9	9	9		9	
L, Recommended Gray Shade Bits	3	3	3	3	3	3	2	3	
n, Recommended No. of range or vertical elements stored	512	512	512	512	512	768	512 (PPI) 128 (E-Scan)	768	51... 12...
Range bin collapsing ratio	3	3	3	2	2	1.2	1.8	1.2	
m, Recommended No. azimuth or horizontal elements stored	128 (B-Scan) 256 (PPI)	128 (B-Scan) 256 (PPI)	128 (B-Scan) 256 (PPI)	128	256	128 (B-Scan) 256 (PPI)	256 (PPI) 256 (E-Scan)	128 (B-Scan) 256 (PPI)	25... 25...
Number of 3 db antenna beamwidth in scan width	43	43	34	33	30	56	75 (Az) 50 (Elev)	56	75 ... 50 ...
Symbol Refresh memory size (kbits)**	131	131	131	65	131	196	131	196	
Sensor Refresh memory size (kbits)	393	393	393	196	393	590	262	590	
Recommended TV raster standard	525	525	525	525	525	875	525	875	
$f_{D/A}$, output D/A frequency (MHz)	5	5	5	2.5	5	8.5	5	8.5	
ω_f, output video rolloff (MHz)	2.5	2.5	2.5	1.2	2.5	4.2	2.5	4.2	

*Requires 40 MHz A/D frequency for E^2-Scan.

**Assume 1 bit level for symbol refresh memory.

TABLE 28. SUMMARY OF MECHANIZATION PARAMETERS

Aircraft/Radar System

...Rdr ...Q-110	FB-111 Attack AN/APQ-114	FB-111 TF Rdr AN/APQ-134	F-5E Attack Rdr APQ 153	F-111D Attack Rdr AN/APQ-128	F-111D TF Rdr AN/APQ-130	F-15 AN/APQ-63	B-1 AN/APQ-144	B-1 Ear	Recommended MMSDS Design Parameters (includes growth)
...I ...n	B-Scan PPI PPI-Exp	PPI TC-PPI E^2-Scan	B-Scan Search Track	B-Scan PPI PPI-Exp Strip Map Patch	PPI TC-PPI E^2-Scan	B-Scan PPI	B-Scan PPI PPI-Exp	B-Scan PPI PPI-Eap Strip Map Patch	B-Scan PPI PPI-Eap Strip Map Patch E^2-Scan TC-PPI
	Gnd Rng Swp			Gnd Rng Swp		Multi Scan Storage Dig Video	Gnd Rng Swp	Gnd Rng Swp Dig Video	Gnd Range Sweep Analog/Digital Video
	1	1	1	2		1	1	2	Any
	7	4		VSD 4 x 6 MSD 7 x 9		4 x 4	7	10	10 Inch Max
	4	2	4	4	2	(2)	4	(4)	4 (modularly expandable to 6)
	2.5	5.0*	2.5	2.5	5.0*	(2.0)	2.5	–	40
	915	915	620	1220	915	256	915	768	2048
	7-80		260	9-50			7-80		6-150
	7/8, 31/32		31/32	7/8, 31/32			7/8, 31/32		7/8, 15/16, 31/32
	9		9	9			9		10
	3	2	3	3	2	3	3	4	programmable truncation to 2, 3 or 4
...1) ...can)	768	512 (PPI) 128 (E-Scan)	512	768	512 (PPI) 128 (E-Scan)	256	768	768	modularly expandable 256-1024 in blocks of 256
	1.2	1.8	1.2	1.6	1.8	1.0	1.2	1.0	peak detection range bin collapsing after integration
...l) ...can)	128 (B-Scan) 256 (PPI)	256 (PPI) 256 (E-Scan)	128	128 (B-Scan) 256 (PPI)	256 (PPI) 256 (E-Scan)	256	128 (B-Scan) 256 (PPI)	768	modularly expandable 128-1024 in blocks of 128
	56	75 (Az) 50 (Elev)	17	59	75 (Az) 50 (Elev)	45	56		
	196	131	65	196	131	65	196	590	
	590	262	196	590	262	196	590	2360	basic memory module: 256 x 256 x 1
	875	525	525	875	525	525	875	875	525 and 875 and 1023
	8.5	5	2.5	8.5	5	2	8.5	25	40
	4.2	2.5	1.2	4.2	2.5	1	4.2	12.5	programmable 1-20 MHz

2

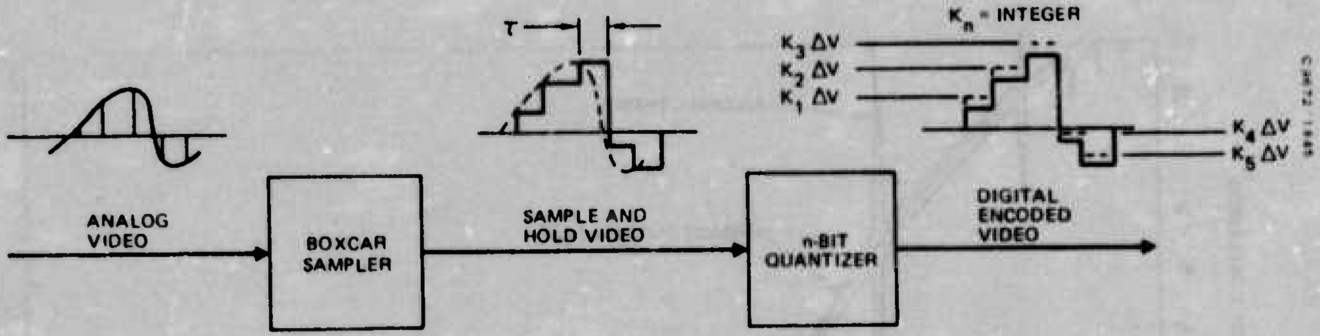


Figure 40. A/D converter.

The Modulation Transfer Function (MTF) of a sampled data system is a function of both the number of samples taken per cycle of input video and the phase relationship of the sampling pulse and the input video. A functional block diagram of the sampling process is shown in Figure 41. The average modulation over all phase angles can be computed analytically and is the magnitude of the Fourier transform of the rectangular pulse response of the boxcar sampler or the function: $\left|\frac{\sin \pi x}{\pi x}\right|$, where x is the ratio of input frequency (N) to sampling frequency (M).

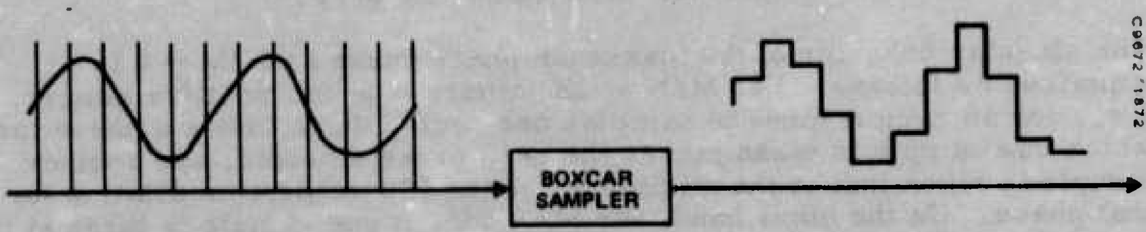


Figure 41. Sampling system.

The maximum and minimum modulation for a specific phase relationship can also be calculated. These three functions; maximum modulation, average modulation, and minimum modulation; are plotted in Figure 42.

Nyquist sampling is represented by $N/M = 1/2$, at which point the average modulation is $2/\pi \approx 65$ percent. There is also a maximum variation of modulation with phase, since the minimum modulation is 0 percent and the maximum modulation is 100 percent. Input frequencies such that $N/M > 1/2$ are subject to aliasing, which means that although the output modulation may be greater than zero, it will be at a lower frequency than the input, resulting in distortion of information.

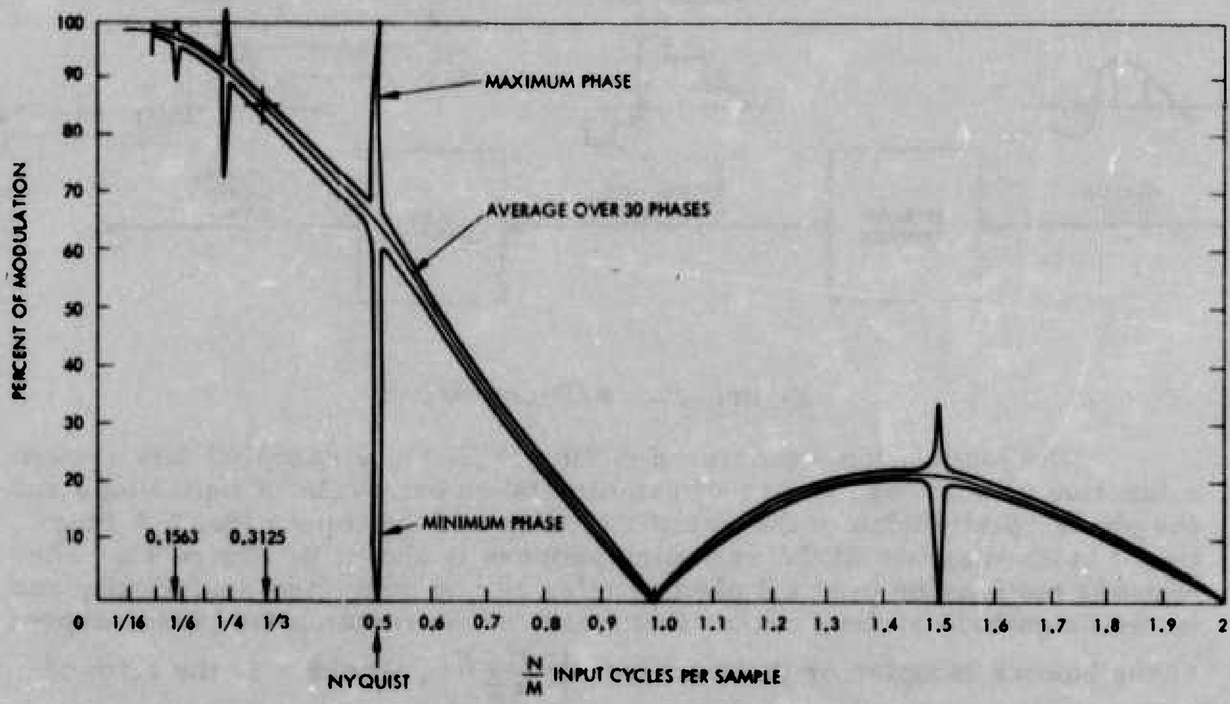


Figure 42. A/D converter MTF.

The singular behavior of the maximum phase curve as N/M → 0 is explained as follows. For M/N = 2K, where K is any positive integer, i.e., for an even number of samples per cycle, there exists a phase for which one sample is taken just at the peak of the sinusoid, and another sample is taken just at the minimum, giving 100 percent modulation for that phase. On the other hand, for M/N odd, if one sample is taken at the peak of the sinusoid, then the following minimum is symmetrically straddled by a pair of samples, so the modulation is less than 100 percent. A similar discussion applies to the minimum phase curve, where there always exists a phase for which two samples are zero if M/N is even, and only one sample can be zero if M/N is odd. As the number of samples taken per cycle becomes large, i.e., as N/M → 0, the effect of one or two individual samples becomes unimportant, so the singularities decrease in amplitude, and all the curves converge to $|\sin \pi x / \pi x|$.

These results can be applied to the computation of display system sinewave MTF's. The magnitude portion of the MTF of a system which is a cascade of several components is the pointwise product of the magnitudes of the MTF's of each of the components in the system. Thus, the display system MTF is multiplied by the sensor MTF to determine the overall system MTF. The display system MTF is the product of the sampler MTF, the processor MTF, and the display MTF. Since the digital memory is discrete in nature beyond the sampler, the memory MTF, M(f) = 1 for all frequencies f passed through the sampler. In other words, there are no further MTF losses beyond the sampler due to the memory in a display system, if sufficient memory elements are provided to store and display all the samples taken. It is also assumed the D/A has a much wider bandwidth than the rest of the system.

A complete display system MTF is the combination of the cascaded A/D converter and display. The MTF in Figure 42 can be converted to a more standard form as follows. Each cycle represents a line pair. There are n resolution bins in a line, say, for a k-inch display. Then at the Nyquist frequency,

$$\frac{1}{2}\ \frac{\text{Input cycles}}{\text{Sample}} \times \frac{\text{1 line pair}}{\text{Input cycle}} \times \frac{n}{k}\ \frac{\text{samples}}{\text{in.}} = \frac{n}{2k}\ \frac{\text{line pairs}}{\text{in.}}$$

For example, assume 768-resolution element samples across a 10-inch rectangular display, so n/2k = 38.4 TV lines per inch is the point on the digital sampling MTF curve corresponding to the 65% MTF response. Assume a gaussian display spot with a 0.010 inch two sigma (2σ) spot width. The MTF response for a gaussian spot is of the form $e^{-2(\pi\sigma f)^2}$, so for f = 38.4 TV lines per inch, the CRT MTF response is 47%. Combination of the two MTFs by multiplication is shown in Figure 43, which represents the display system modulation transfer characteristic.

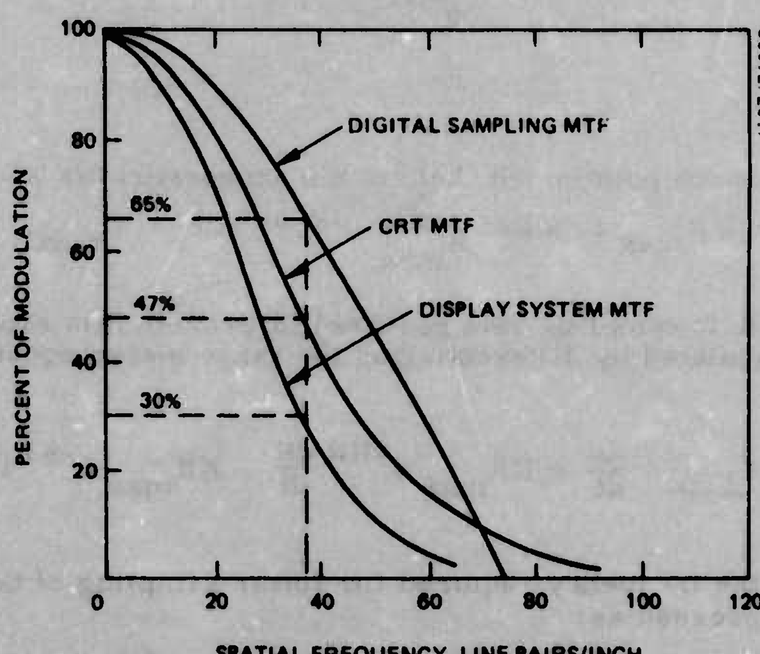


Figure 43. DSC/display system sine MTF

In most radar modes, a fixed A/D sampling clock is used for each radar range scale. However, there are two special modes requiring a time varying clock rate as a function of radar range. These modes are the terrain following E-Square format and the ground range sweep corrected format. A similar sampling function is required for a Line Scan EO sensor. These clock generation functional requirements are discussed in the following paragraphs.

E-Square Scan

The E-Square Scan format provides an exponential range sweep display presentation to expand the near range portion of the video returns. This is done to provide high resolution at near range as well as display of terrain in the flight path at longer ranges. The range sweep on the display is usually of the form

$$X = R_{max}(1 - e^{-KR})$$

where X is the distance on the display, R_{max} is the maximum range (usually 10 miles), R is the instantaneous range and K is the appropriate scale factor. For example, if it is desired to expand the first mile to one-half the display width, then for $X/R_{max} = 1/2$ at R = 1 mile

$$e^{-Kx1} = 1/2$$

$$K = 0.7$$

It must be pointed out that in this expression for X, K must be greater than $3/R_{max}$ to allow $\frac{X}{R_{max}} > 0.95$ at $R = R_{max}$.

The A/D sampling rate required to provide this exponential range sweep is calculated by differentiating the range sweep equation:

$$f_{A/D} = \frac{dx}{dt} = KR_{max}\, e^{-KR} \frac{dR}{dt} = KR_{max}\, e^{-KR} f_o$$

where f_o is the frequency required for linear sampling of the range sweep. f_o can be expressed as:

$$f_o = \frac{N}{R_{max} \cdot 12.36 \times 10\text{-}6}$$

where N equals the total number of range samples across the display. The expression for $f_{A/D}$ is plotted in Figure 44 for several values of N assuming R_{max} = 10 nautical miles and K = 0.7.

Ground Range Sweep Correction

In most radar ground mapping applications, a constant range sampling interval during the radar range sweep is used. This results in equal intervals of slant range which are displayed to the user. Since the slant range to a point on the ground is not equal to the ground range to that point, the displayed ground map is distorted by an amount proportional to the discrepancy between the slant range and the ground range to any particular point. Thus it may be desired to vary the duration of the range sampling interval in such a way as to result in equal intervals of ground range displayed to the user, thereby eliminating ground map disotrtion.

The geometry of the problem is shown in Figure 45. The aircraft is flying straight and level over relatively flat terrain at an altitude h. Slant range is designated R^s while ground range is designated R^g. The ground range is divided into N equal intervals.

For small $\Delta\theta_K$

$$\Delta R_K^S = \frac{R^g \cos\theta_K}{N} = \left(\frac{R^g}{N}\right)^2 \frac{K}{\sqrt{h^2 + \left(\frac{KR^g}{N}\right)^2}}$$

(where K represents an integer number of range bins)

since

$$\frac{R^g}{N} = \Delta R^g$$

Then

$$\Delta R_K^S = \frac{\Delta R_K^g}{\sqrt{1 + \left(\frac{h}{K\Delta R^g}\right)^2}}$$

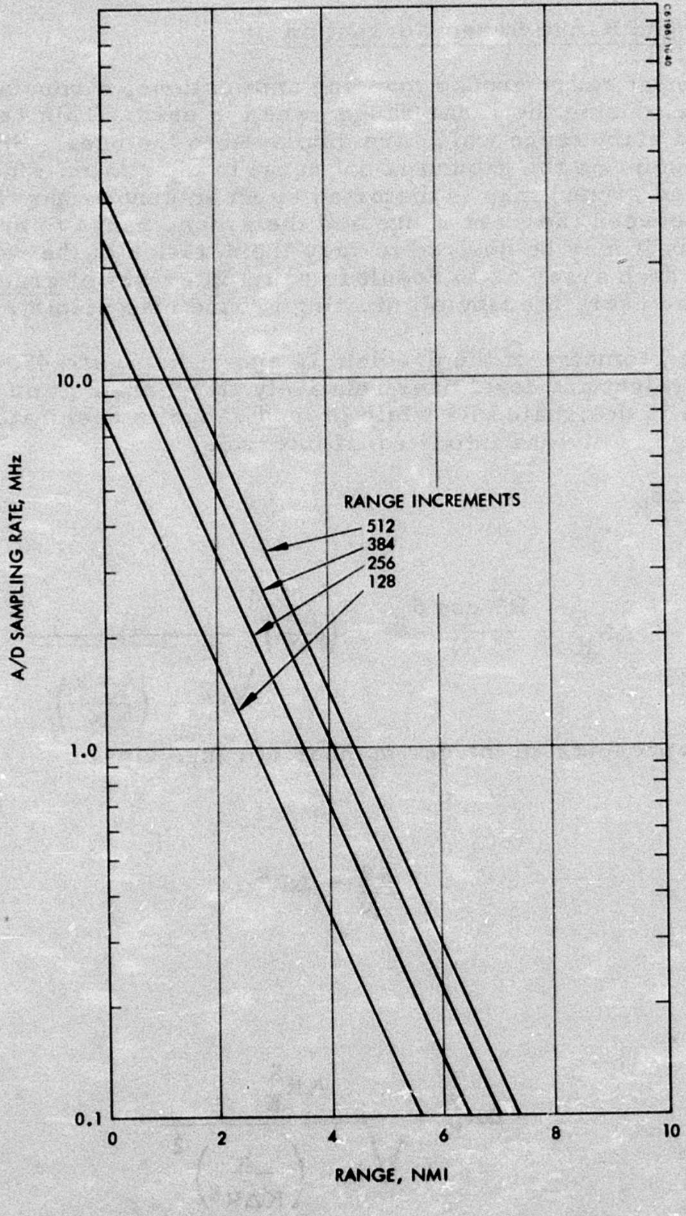


Figure 44. A/D sampling rate as a function of range for exponential scan display.

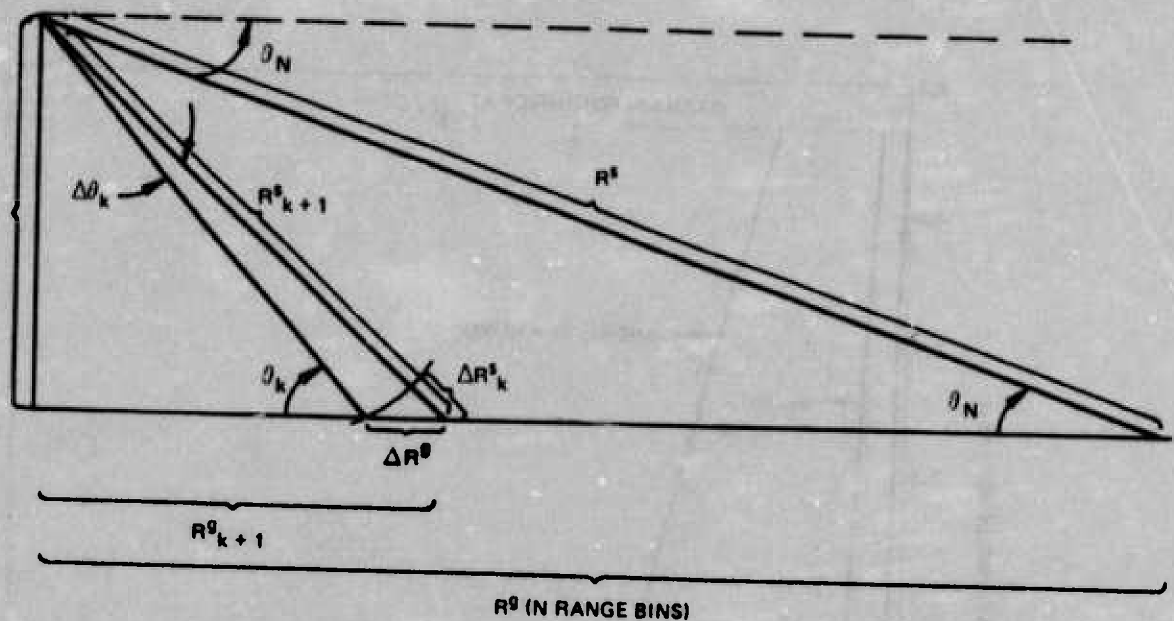


Figure 45. Ground range sweep correction geometry.

Since $\Delta R_K^S = \frac{c\,\Delta t_K}{2}$ where C is the speed of light,

then

$$f_K = \frac{1}{\Delta tk} = \frac{c\sqrt{1 + \left(\frac{2h}{ct}\right)^2}}{2\Delta R^g}$$

This is plotted for $\Delta R^g = \frac{R^g}{512}$ for various values of h for $R^g = 10$ miles and $R^g = 100$ miles in Figures 46 and 47.

<u>E-O Line Scan Sampling</u>

A similar problem to that of the ground range sweep correction arises with a down looking electro-optical sensor. The problem is to derive a video sampling frequency which will provide a display for a down-looking EO line scan with uniform ground sampling intervals as shown in Figure 48. The EO sensor scans at a constant angular rate (ω) directly below the aircraft. To determine the x direction sampling the scan rate and altitude must be known.

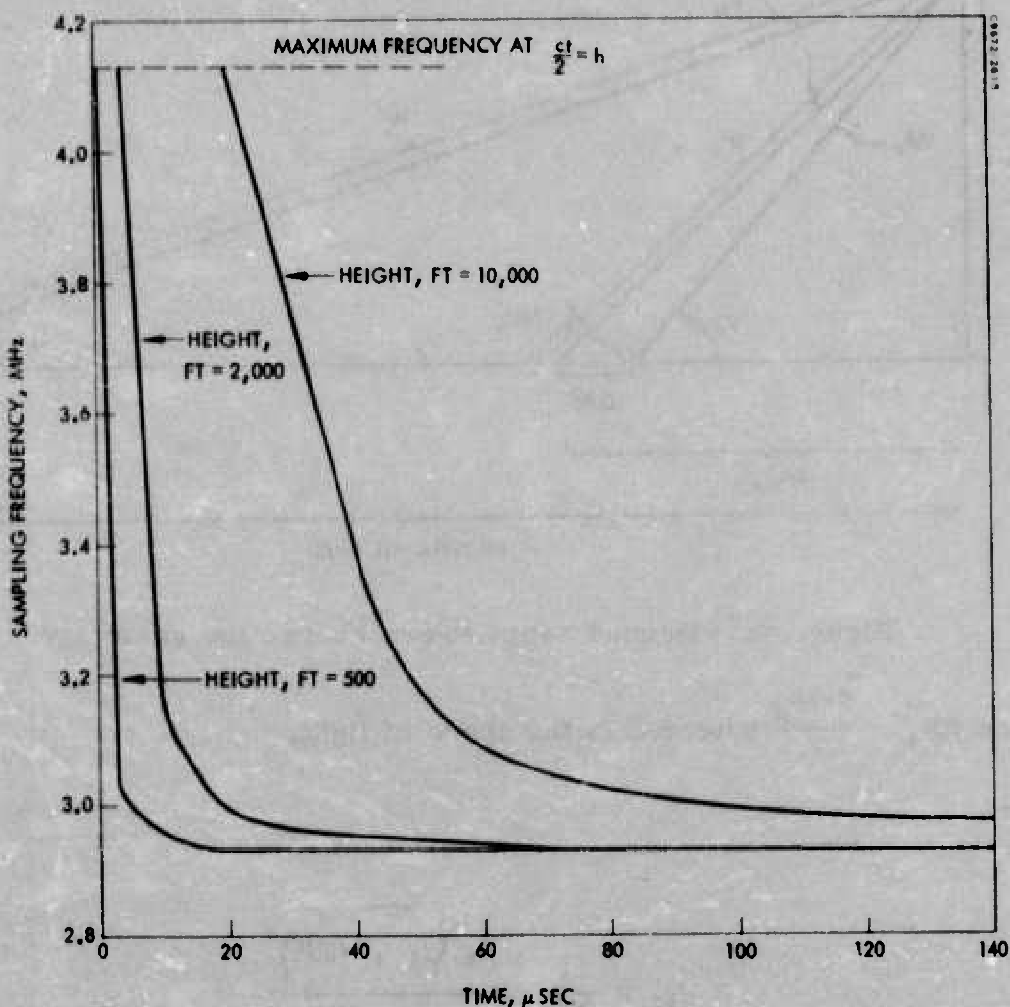


Figure 46. 10-mile ground range sampling requirement.

The sampling frequency needed to obtain equally spaced samples in the x direction is given by:

$$f_x = \frac{h\omega}{\Delta x} \cdot \frac{\cos\theta}{\cos\psi}$$

where

Δx is the resolution increment chosen in the x-direction

ω is the angular scan rate of the sensor

h is the height of the aircraft

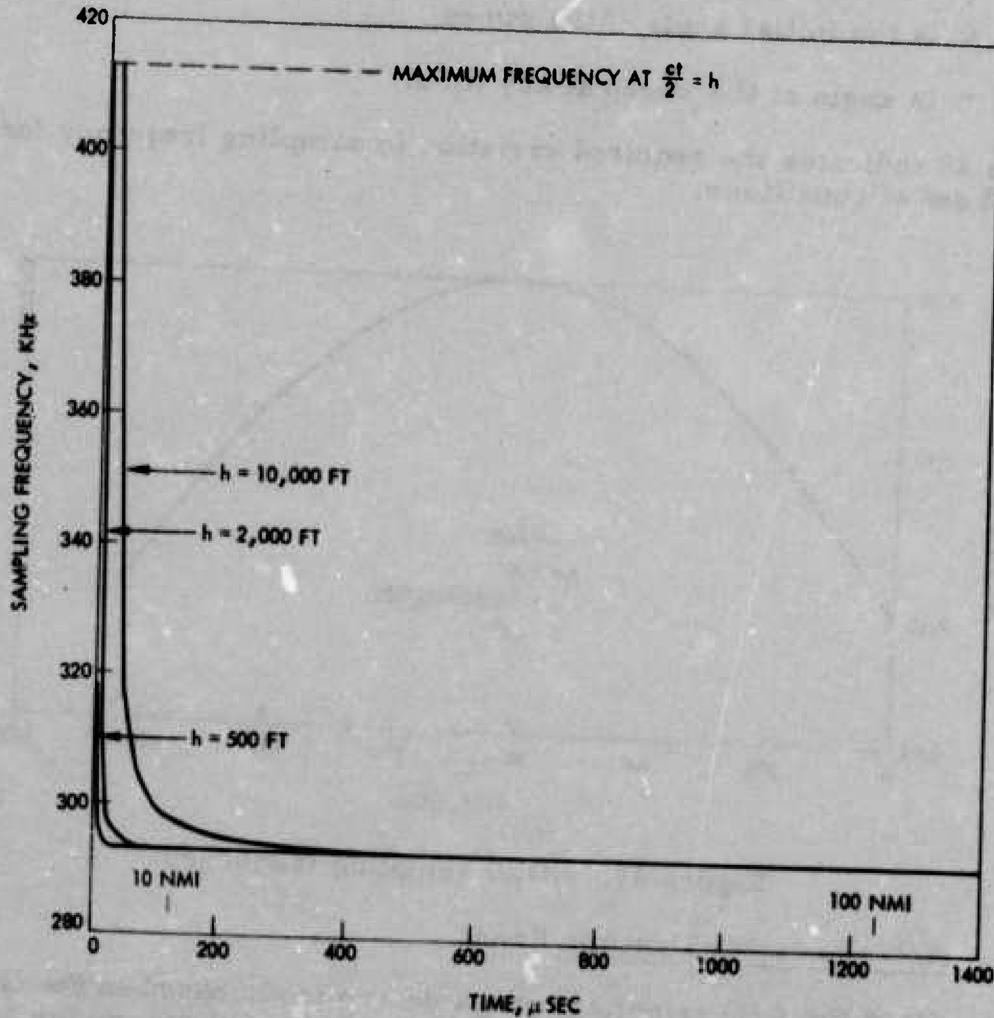


Figure 47. 100-mile ground range sampling requirement.

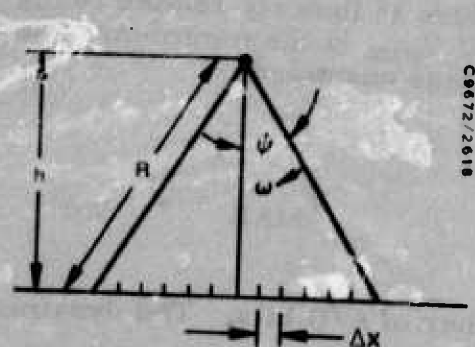


Figure 48. Geometry of downward looking line scan sensor.

ψ is the initial angle of the sweep

θ is angle of the sweep at any time.

Figure 49 indicates the required variation in sampling frequency for a typical set of conditions.

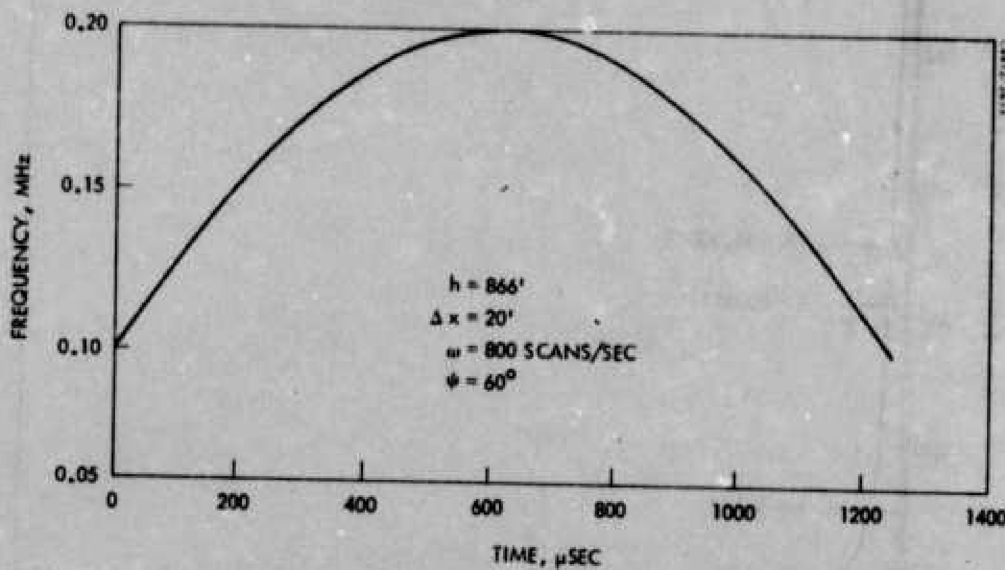


Figure 49. EOLS sampling frequency.

3.2.2 A/D Converter Dynamic Range

Once the A/D sampling rate is determined, based on the frequency response of the sensor video, the other major design parameter for the A/D is the number of bits required to encode the video dynamic range. Assuming the A/D converter is a linear process which produces a binary output whose magnitude is linearly related to the magnitude of the analog input voltage, then if V_{min} is the minimum voltage quantization and V_{max} is the maximum voltage quantized

$$V_{MAX} = 2^n V_{MIN} \quad ,$$

where n is the number of A/D bits. The dynamic range of the video is by definition

$$K = 20 \log_{10} \frac{V_{max}}{V_{min}} = 20\, n \log_{10} 2 = 6.02\, n \text{ (db)}$$

Therefore, the dynamic range of the A/D converter is equal to approximately 6 db times the number of A/D bits. This relationship is tabulated in Table 29. Conventional television displays have dynamic ranges of 25 to 30 db for example, thereby requiring 4 to 5 bits of dynamic range encoding.

TABLE 29. DYNAMIC RANGE AS A FUNCTION OF A/D BITS

n	Dynamic Range = K, db
1	6.02
2	12.04
3	18.04
4	24.08
5	30.10
6	36.12
k	6.02 k

3.2.3 Sampling Noise

This noise is introduced by quantization in time. Information is lost between sample points and, intuitively, the sampling pulse width should be kept small to avoid distortion of the sampled signal frequency spectrum.

The input signal transform is multiplied by the sample and hold circuit transform with a resultant system transfer function as shown in Figures 50 and 51. Mathematically, the system transform is expressed:

$$X_s^h(f) = X_s(f)\, H(f)$$

If the sample pulse time is short with respect to the sample spacing, i.e., $\tau \ll 1/2\omega_s$, or $1/- \gg 2\omega_s$, the Fourier spectrum of $X_s^h(t)$ is as shown in Figure 50. Observe that in this case, the first lobe of the sample and hold transfer function, H(f) is much wider than the lobe of the input transfer function and therefore the input signal is not appreciably distorted from that of $X_s(f)$, which is identical to the input spectrum X(f). The reconstructed signal will be close to the original input signal X(t). However, now consider the case where the pulse width is equal to the sample spacing, i.e., $\tau = 1/2\omega_s$ or $1/\tau = 2\omega_s$. Then the Fourier spectrum of $X_s^h(f)$ is shown in Figure 51. Note in this case that the sample and hold transfer function, H(f), is now roughly comparable in width to the input, $X_s(f)$, so that $X_s^h(f)$

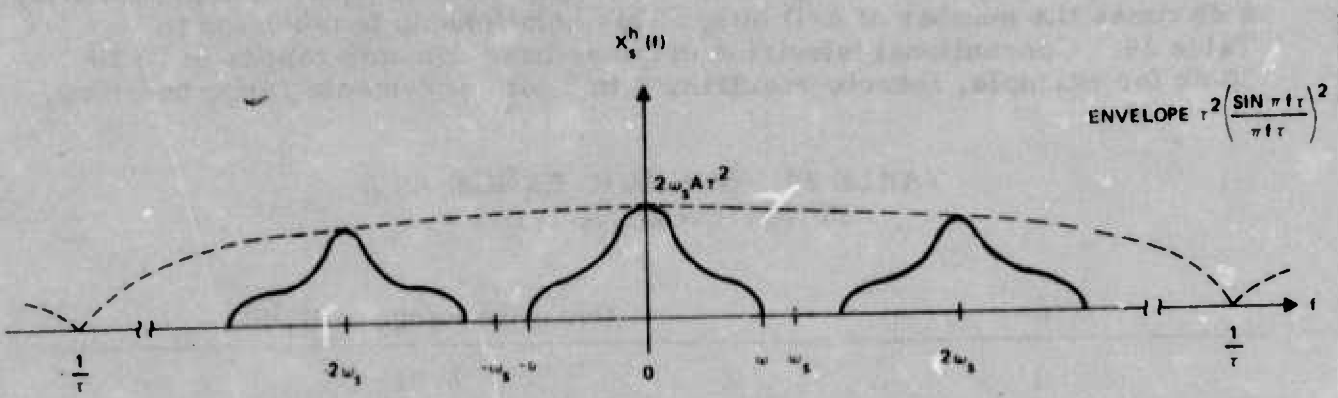


Figure 50. Sampled signal spectrum, short hold pulse.

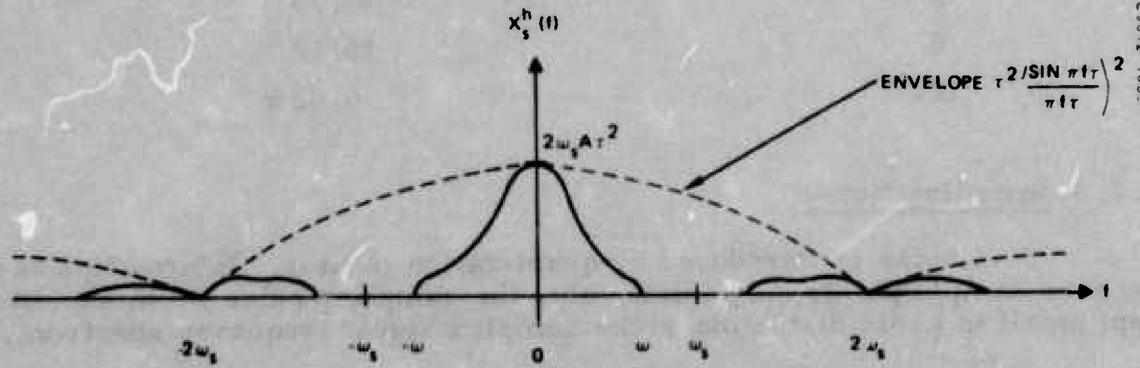


Figure 51. Sampled signal spectrum, long hold pulse.

is significantly distorted from that of $X_s(f)$, particularly at the higher frequencies. This means that edge and detail information can be attenuated appreciably in the reconstructed signal X(t).

This latter is the normal situation in a digital scan converter where the output video to the CRT is "box car" video (i.e. the video pulse width is equal to the sample spacing). This should not be confused with the sampling aperture time at the input to the A/D converter which should be kept as short as possible.

The noise power introduced by the sample and hold process is

$$P_s = \int_{-\omega_s}^{+\omega_s} \left| X(f) - X_s^h(f) \right|^2 df,$$

where X(f) is the spectrum of the input signal and $X_s^h(f)$ is the spectrum of the signal at the output of the boxcar sampler.

Since

$$X_s^h(f) = X_s(f)\ H(f) \quad ,$$

where

$$H(f) = \tau \left(\frac{\sin \pi f \tau}{\pi f \tau} \right) \quad ,$$

and

$$X_s(f) = X(f) \qquad \text{for } |f| \leq \omega_s$$

then,

$$P_s = \int_{-\omega_s}^{+\omega_s} \left| X(f) - \frac{X(f)\ H(f)}{\tau} \right|^2 df = \int_{-\omega_s}^{+\omega_s} \left| X(f) \right|^2 \left| 1 - \frac{H(f)}{\tau} \right|^2 df$$

The noise introduced by sampling is seen to be a function of the input signal frequency spectrum and the sample pulse width, assuming the Nyquist sampling criteria is satisfied. The noise power is plotted as a fraction of the input signal power, S_i^2, in Figure 52 as a function of the relative sampling frequency, ω_s/ω where $\omega_s = 1/\tau s$ and $\omega = 1/\tau$. The signal is assumed to be a rectangular pulse of width τ.

As seen in Figure 52, one sample per input pulse width introduces sampling noise equal to 2 percent of the input signal power. Two samples per pulse reduces the sampling noise to 0.5 percent of the input signal power.

3.2.4 Quantization Noise

Assume an n-bit quantizer in the A/D converter. Then the input signal, S_{max}, will be broken into 2^n discrete amplitude levels. Assume further that the input pulse train has amplitudes which are equally likely over the range of the converter. Since the uniform distribution represents a

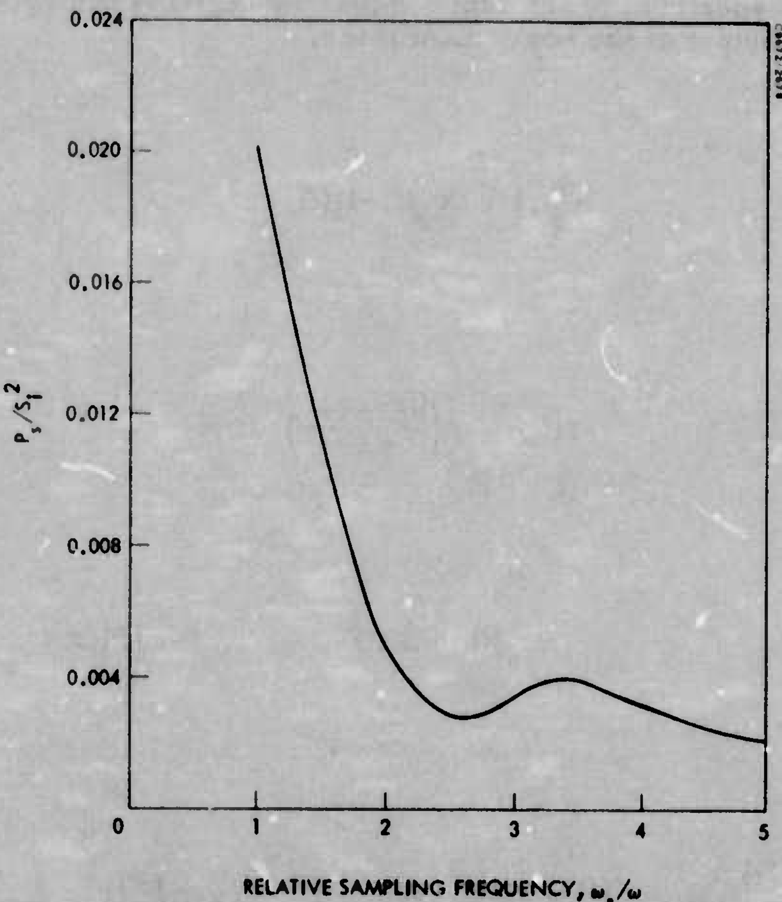


Figure 52. Ratio of sampling noise power to signal power, rectangular pulse.

worst case situation, analysis with realistic input amplitude distributions should yield larger SNRs. The quantization errors q are uniformly distributed, and their variance, is

$$\sigma_q^2 = \frac{2^{-2n}}{12} S_{max}^2 \quad .$$

The noise power due to quantization, assuming a stationary noise process and a nearest level quantizer with a mean noise level equal to zero is therefore

$$P_Q = \sigma_q^2 = \frac{2^{-2n}}{12} S_{max}^2 \quad .$$

3.2.5 Total Noise

The noise power due to the cascading of the two elements of the A/D converter are calculated by summing the power of each. The RMS noise for the system is thus

$$P_{RMS_{A/D}} = \left[\frac{2^{-2n}}{12} S_{max}^2 + P_s\right]$$

since time quantization and amplitude quantization are independent, random processes.

Given an input signal with signal to noise ratio S_i^2/σ_i^2, where σ_i^2 represents the input noise power, and S_i^2 represents the RMS power of a deterministic signal, the output noise variance is given by

$$\sigma_0^2 = \sigma_i^2 + \frac{2^{-2n}}{12} S_{max}^2 + P_s$$

and computing the output SNR,

$$\frac{S}{N}_o = \frac{S_i^{\,2}}{\sigma_i^{\,2} + \frac{2^{-2n}}{12} S_{max}^{\,2} + P_s} =$$

$$\frac{S_i^{\,2}}{\sigma_i^{\,2}}\left[1 + \frac{2^{-2n}}{12} \cdot \frac{S_{max}^{\,2}}{S_i^{\,2}} \left(\frac{S_i^{\,2}}{\sigma_i^{\,2}}\right) + \frac{P_s}{S_i^{\,2}} \cdot \left(\frac{S_i^{\,2}}{\sigma_i^{\,2}}\right)\right]^{-1}$$

The change in input SNR expressed in db is thus

$$\Delta SNR = 10 \log\left(\frac{S}{N}\right)_o - 10 \log\left(\frac{S}{N}\right)_i$$

and

$$\Delta SNR = -10 \log \left[1 + \frac{2^{-2n}}{12} \frac{S_{max}^2}{S_i^2} \left(\frac{S_i^2}{\sigma_i^2} \right) + \frac{P_s}{S_i^2} \left(\frac{S_i^2}{\sigma_i^2} \right) \right]$$

The signal to noise ratio decrement is a function of the quantization interval (2^{-n}), the input SNR $\left(\frac{S_i^2}{\sigma_i^2}\right)$, and the sampling process (P_s). Figure 53 shows a plot of ΔSNR as a function of the input SNR for sampling intervals corresponding to 1, 2, 3, and 4 bits and for values of P_s corresponding to one sample per pulse width and two samples per pulse width. Thus, Figure 53 may be used to determine the degradation in SNR from the sampler and the quantizer. (In Figure 53 the assumption that $\frac{S_{max}^2}{S_i^2} = 10$ is made.

Assuming, an input SNR of 0 db, a quantization of 4 bits and one sample per pulse width, a loss in SNR of 0.1 db due to A/D conversion is experienced. The quantization noise introduced by the digitization process is seen to be negligible for 3 or 4 bit quantization.

3.3 <u>Digital Video Integrator</u>

An integrator in the digital display system can be used to improve the signal to noise ratio of the video. It can be used in a number of different ways and applied to several sensors. For example, for a FLIR sensor with a high frame rate, integration from frame to frame may be desirable. Also in a low PRF B-scan radar mode, the integrator can be used to collapse the several thousand input sweeps in one radar scan to the few hundred necessary to preserve resolution. Used in this way, the signal to noise ratio improvement results in better operator target detection performance. In fact, target detection studies performed at Hughes have indicated that targets as small as 3 db below the residual noise level could easily be detected when stored and displayed in a B-scan format through a digital scan converter with a video integrator at the input. In the PPI mode, the integrator serves to eliminate scintillation from sweep to sweep.

A block diagram of a line-by-line digital integrator is shown in Figure 54. It consists basically of a serial shift register memory to hold the accumulated sum of the video as it is shifted in element by element. Every time a new range sweep is clocked into the system, the stored sum is reduced by a multiplying factor in a feedback loop and added element by element to the new quantized video.

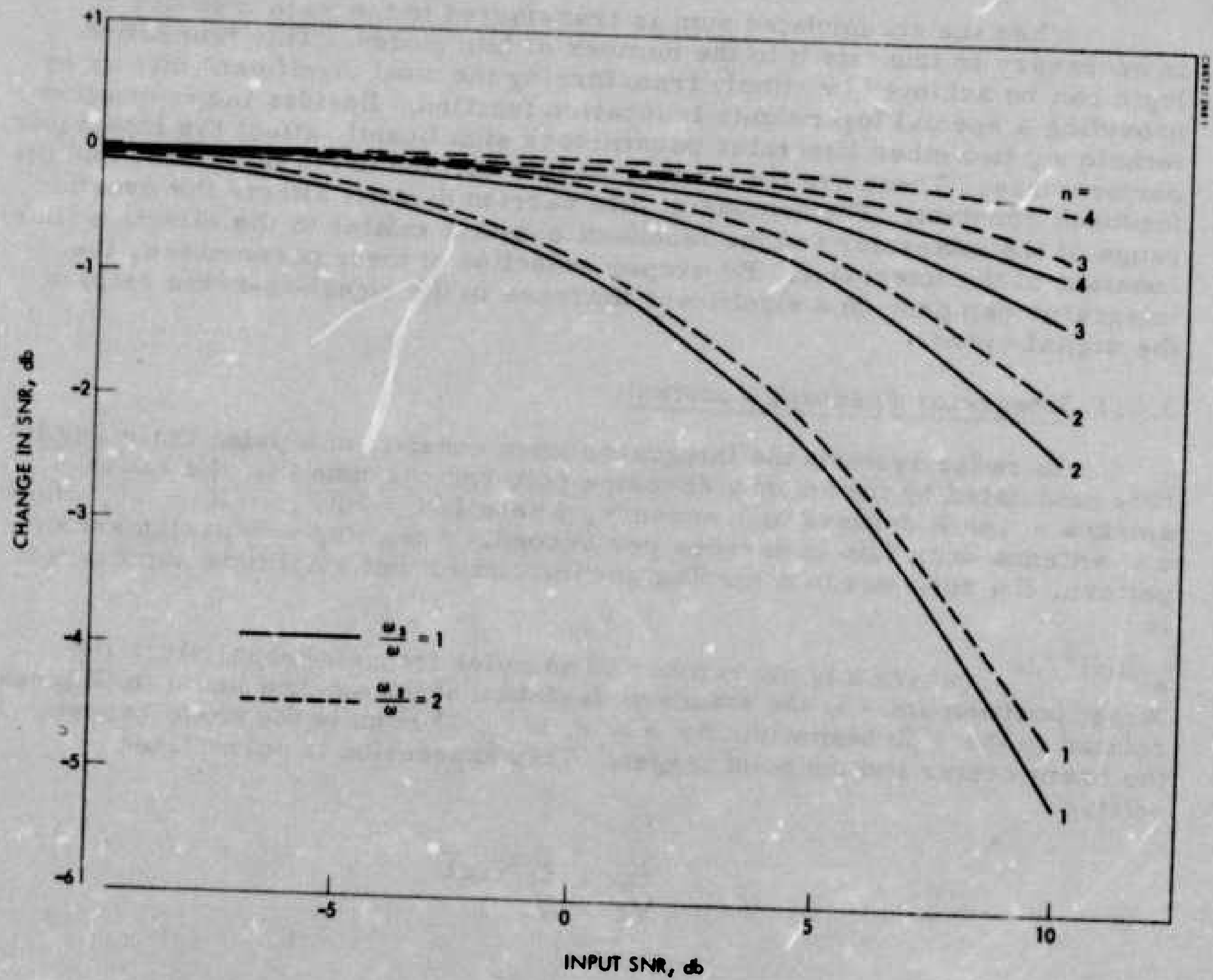


Figure 53. Effect of digitization on system signal-to-noise ratio.

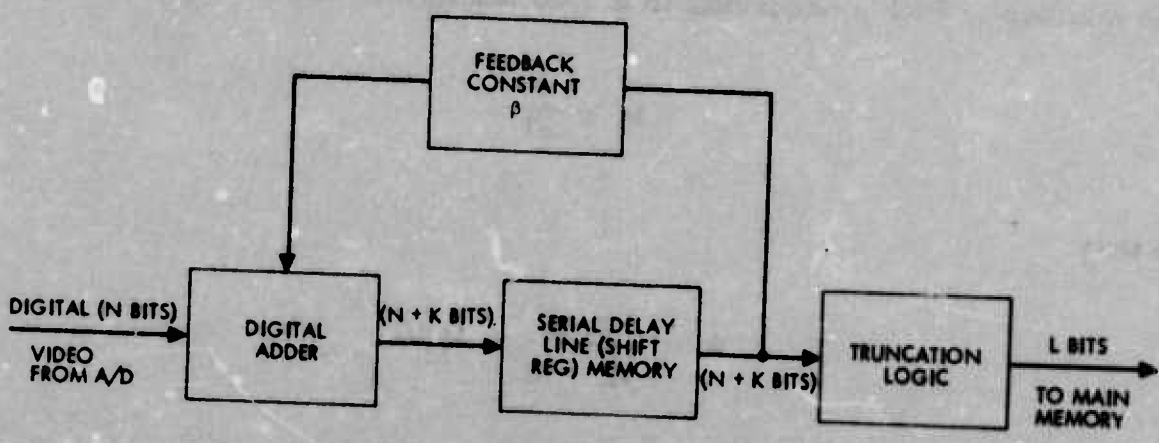


Figure 54. Digital video integrator.

When the accumulated sum is transferred to the main memory it is necessary to truncate it to the number of bits stored. This truncation logic can be achieved by simply transferring the most significant bits or by providing a special logarithmic truncation function. Besides the truncation technique, two other integrator parameters significantly affect the integrator performance. These are the number of bits carried in the integrator and the feedback constant. The number of bits carried directly affects the dynamic range of the integrator and the feedback constant relates to the effective time constant of the integrator. By proper selection of these parameters, the integrator can provide a significant increase in the signal-to-noise ratio of the digital video.

3.3.1 Integrator Feedback Constant

In radar systems the integrator input consists of a pulse train amplitude modulated by the antenna envelope pattern. Assume that the radar antenna scans X degrees in T seconds, where $1/T = PRF$, so $X = \omega T$, where ω = antenna scan rate in degrees per second. Assuming a Gaussian antenna pattern, the response to nonfading unscintillating unit amplitude point target is

$e^{-(nx)^2/2\sigma^2}$, where n is the number of samples (range sweeps) since the target position and σ is the standard deviation of the antenna beam in degrees, related to the 3 db beamwidth by $\Gamma = 2.35\sigma$. Then nx is the angle between the beam center and the point target. This expression is normalized by setting

$$\phi = \frac{X}{\sigma\sqrt{2}} = \frac{2.35\,\omega T}{\sqrt{2}\,\Gamma}$$

so that $e^{-(nx)^2/2\sigma^2} = e^{-(n\phi)^2}$

The number of PRF's occurring in a 3 db beamwidth can be expressed as

$$M = \frac{\Gamma}{\omega T}$$

so that

$$\phi = \frac{2.35}{\sqrt{2}\,M} = \frac{1.67}{M}$$

If the integrator has a feedback loop constant β, where $|\beta| < 1$ for stable operation, then a figure of merit q for the integrator can be expressed as

$$q = \frac{\ln\beta}{\phi}$$

The signal-to-noise ratio improvement factor is expressed as (reference 8, Cooper)

$$F_i = F_I \, f_i \, (q, \theta_N)$$

where F_I is the ideal improvement factor, obtainable in theory with a matched filter, and is given by

$$F_I = \frac{1}{\sqrt{\phi}} \sqrt[4]{\frac{\pi}{2}} = \sqrt{\frac{M}{1.67}} \sqrt[4]{\frac{\pi}{2}} = 0.87 \sqrt{M}$$

and

$$f_i (q, \theta_N) = \sqrt[4]{\frac{\pi}{2}} \, e^{-\theta_N^2} \sqrt{-q} \; e^{\left(\frac{q}{2} + \theta_N\right)^2} \left[1 + \operatorname{erf}\left(\frac{q}{2} + \theta_N\right)\right]$$

In the above expression, θ_N is the angle between the direction of the point target and the direction of the radar antenna boresight. The optimum value of θ_N can be regarded as a measure of the time which must elapse after the arrival of the waveform containing the maximum signal, before the output signal/noise ratio reaches its peak value.

The maximum or ideal improvement factor, F_I, is seen to be directly proportional to the square-root of the number of samples or PRF's contained in the 3 db antenna beamwidth. The actual improvement factor is a function of the feedback constant as expressed in f_i (q, θ_N). A plot of $f_{i\,max}$ for fixed values of q is shown in Figure 54. Note that as the magnitude of q increases, the improvement figure increases until $|q| = 0.70$ at which point the improvement figure begins to decrease. Thus to maximize the output SNR, the feedback constant, β, should be selected to provide a = -0.7. Since $q = \ln\beta/\phi$, then

$$\beta_{opt} = e^{-0.7\phi} = e^{\frac{1.67}{M}}$$

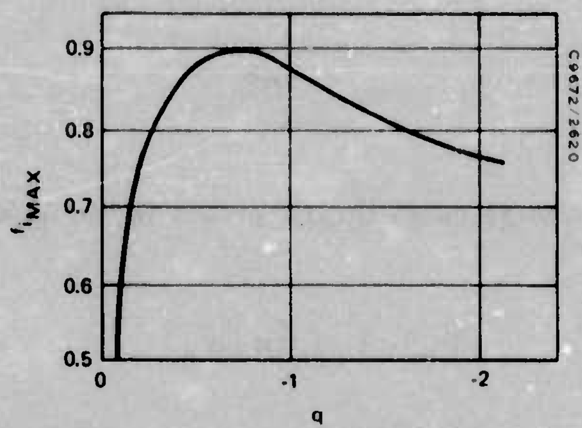


Figure 55. Maximum value of f_i (q, θ_n) as a function of q.

It is most convenient to mechanize β, digitally in the form of $\frac{2^n - 1}{2^n}$. Therefore, β assumes discrete values, 1/2, 3/4, 7/8, 15/16, etc. A plot of the SNR improvement factor in db as a function of M (the number of samples in a 3 db beamwidth), for various values of β is shown in Figure 55. The following example illustrates the use of this figure.

A specific radar has two prf's: 330 and 1060 Hz. With an antenna scan rate of 120 degrees per second and a 3 db antenna beamwidth of 2.8 degrees, the number of pulses in one 3 db beamwidth is ≈ 8 at 330 prf and ≈ 25 at 1060 prf. Using Figure 56, for M = 8, the optimum feedback constant is β = 7/8 and the SNR improvement factor is 6.8 db. For M = 25, the optimum feedback constant is β = 31/32 and the SNR improvement factor is 11.8 db. However, if a single feedback constant of β = 15/16 were used for both prf's, then the resultant SNR improvement factors would be 6.5 db at 330 prf and 11.7 db at 1060 prf or a difference of only -0.3 and -0.1 db respectively from the optimum. Thus, a single feedback constant of 15/16 is adequate for this specific radar application.

The range of values of M for a fixed value of β which provides a SNR improvement factor within 0.5 db of the optimum is given in Table 30.

3.3.2 <u>Accumulator Bits</u>

To prevent saturation of the integrator, sufficient bits to encompass the accumulated integrator sum must be provided. The total bits required are N + K where N is the initial digital video bits from the A/D converter and K is the additional bits required in the integrator to handle the total

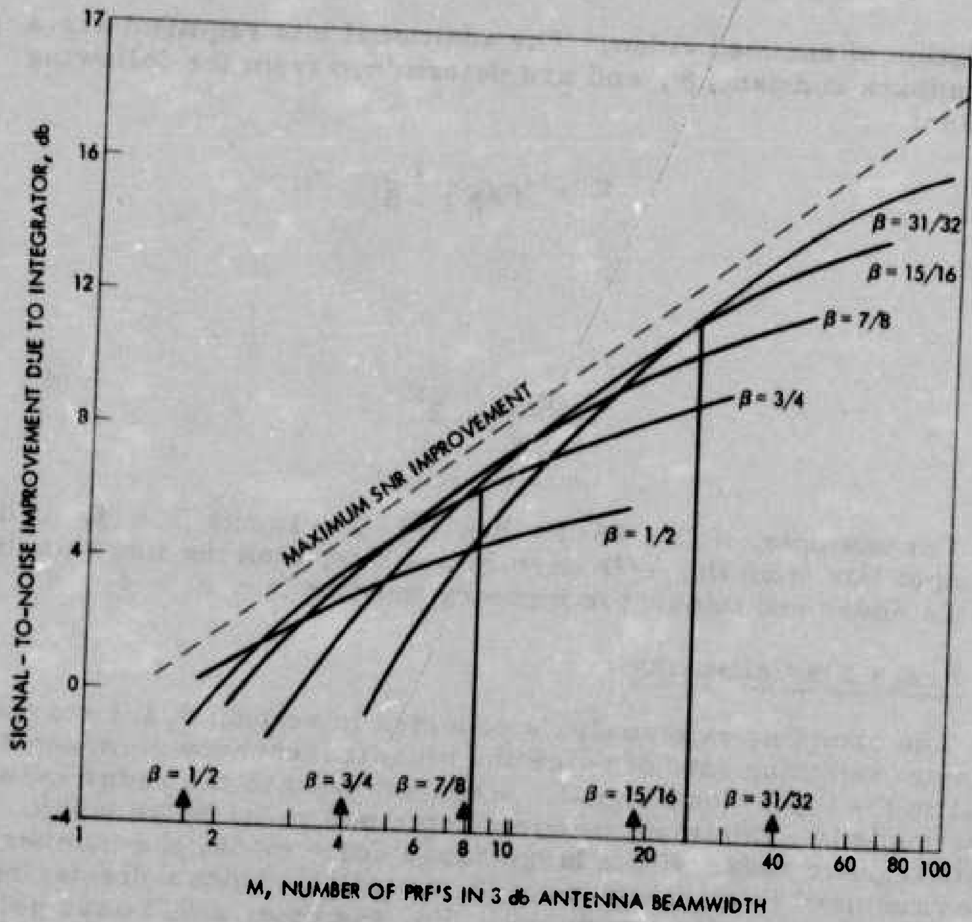


Figure 56. SNR improvement with integration.

TABLE 30. RANGE OF VALUES OF M WHICH MAINTAIN SNR IMPROVEMENT FACTOR WITHIN 0.5 db OF OPTIMUM

β	M
1/2	1 - 3
3/4	2 - 7.5
7/8	3 - 16
15/16	7.5 - 30
31/32	16 - 80

accumulation of summed video. The additional bits required are a function of the feedback constant, β, and are determined from the following expression:

$$K = \log_2 \frac{1}{1 - \beta}$$

or

$$\frac{1}{1 - \beta} = 2^K$$

For example, if $\beta = 15/16$ then $1/1 - \beta = 16$ and $K = 4$. If the initial input bits from the A/D were $N = 4$ bits, then the total number of bits in the adder and integrator memory must be $N + K = 4 + 4 = 8$.

3.3.3 Range Bin Collapsing

The sampling rate analysis provided in section 3.2.1 recommended a minimum sampling rate of twice the highest frequency component of interest in the input video signal. When extended to the radar case, this criteria leads to a minimum of one sample per radar pulse width. Thus for a short pulse radar with a large range scale mode, the number of samples required to be stored may be unrealistic from a display resolution or operator visual acuity standpoint. For example, a 0.5 μsec pulse in a 50 mile range scale would require over 1200 samples in range to be stored. If this were to be displayed on a 5 inch display monitor, then the observers' visual acuity limit would reduce the useable resolution on the display to approximately 500 range samples. Therefore, to minimize the digital scan converter memory requirements, the input video sampling should be collapsed to match the effective display resolution.

This range bin collapsing can be mechanized in three ways: pulse averaging ahead of the integrator, peak detection ahead of the integrator and peak detection after the integrator. The first two methods result in an integrator which stores the same number of range bins as the scan converter main memory, whereas the third method requires an integrator which stores the total number of range bins required by the optimum sampling criteria.

Pulse Averaging

The pulse averaging can be mechanized with a simple pulse stretching filter ahead of the A/D converter or with a digital adder after the A/D conversion. In either mechanization, the effective result is the same assuming the A/D sampling rate and dynamic range is adequate for the signal frequency and dynamic range. The pulse stretching filter computes the average voltage in each group of ρ range samples thereby reducing the signal content. As a worst case, it is assumed that only one independent sample will contain the signal plus noise while the other samples contain noise only. When a target is present, the storage cell representing the range interval surrounding the target will contain the addition of the signal plus noise sample to p-1 noise samples. Averaging will increase the noise to p times the input noise. Therefore, the effective output signal-to-noise ratio is 1/p times the input signal-to-noise ratio. This is equivalent to a decibel loss in the signal-to-noise ratio of 20 log (p). This loss is plotted in Figure 57 as a function of the collapsing ratio p.

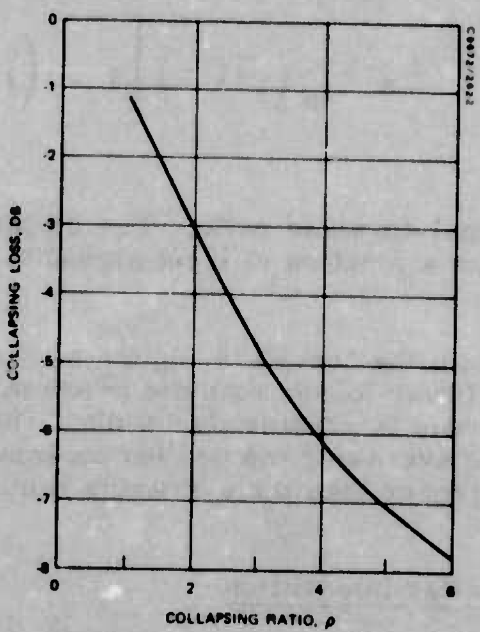


Figure 57. Loss in signal/ noise ratio using averaging technique for range collapsing.

Peak Detection before Integration

The peak detector examines each of p consecutive range bins from the A/D converter, selects the one of largest magnitude, and sends this value to the digital integrator. The collapsing loss is

$$\text{db loss} = 10 \log P_s$$

where P_s is the probability of correct selection of the cell containing the signal plus noise or in other words, P_s is the probability that the signal plus noise exceeds the noise in the adjacent cells examined by the peak detector.

$$P_s = 1 - P_{IS}$$

where P_{IS} is the probability of incorrect selection, It can be shown that P_{IS} is a function of both the collapsing ratio and the input signal-to-noise ratio and is of the form:

$$P_{IS} = \int_0^\infty x e^{-x^2/2} e^{-\lambda} I_o \left(\sqrt{2\lambda}\, X\right) \left[1 - \left(1 - e^{-x^2/2}\right)^{p-1}\right] dx$$

where λ is the input signal-to-noise ratio. The db loss due to peak detecting is plotted in Figure 58 as a function of input signal to noise ratio for various collapsing ratios, ρ.

It is apparent from the curves in Figure 58 that the peak detector results in significantly lower losses than the averaging method for signals whose signal-to-noise ratio is greater than 0 db. The peak detector performance is equal to the averaging method for an input SNR of 0 db and the peak detector is much poorer than the averaging method for targets whose SNR is less than 0 db.

Peak Detection after Integration

One method of taking advantage of the improved peak detector performance is to use the peak detector after the integrator. This means that the integrator must store all the input range samples and perform the collapsing after integration. This enables the targets with SNR less than 0 db to be integrated up to a SNR above 0 db and then peak detected. This approach is the optimum from the standpoint of maximizing the SNR but requires a much larger integrator (for example, 1200 range bins versus 500 range bins). The choice of the range bin collapsing method is therefore dependent on the expected input signal-to-noise ratio and the integrator mechanization constraints. An example of the overall SNR at the output of the integration-range bin collapsing network for two targets is given in Table 31. This example assumes a collapsing ratio $\rho = 3$ and an integrator improvement factor of 12 db.

As seen in Table 31, there is little difference between peak detection before or after integration for a large target SNR. However, for a small target SNR, there is significant improvement in SNR employing peak detection after integration.

3.3.4 Dynamic Range Compression

From the discussion of the video integrator, it is seen that the dynamic range of the digital video integrator output may be much higher than

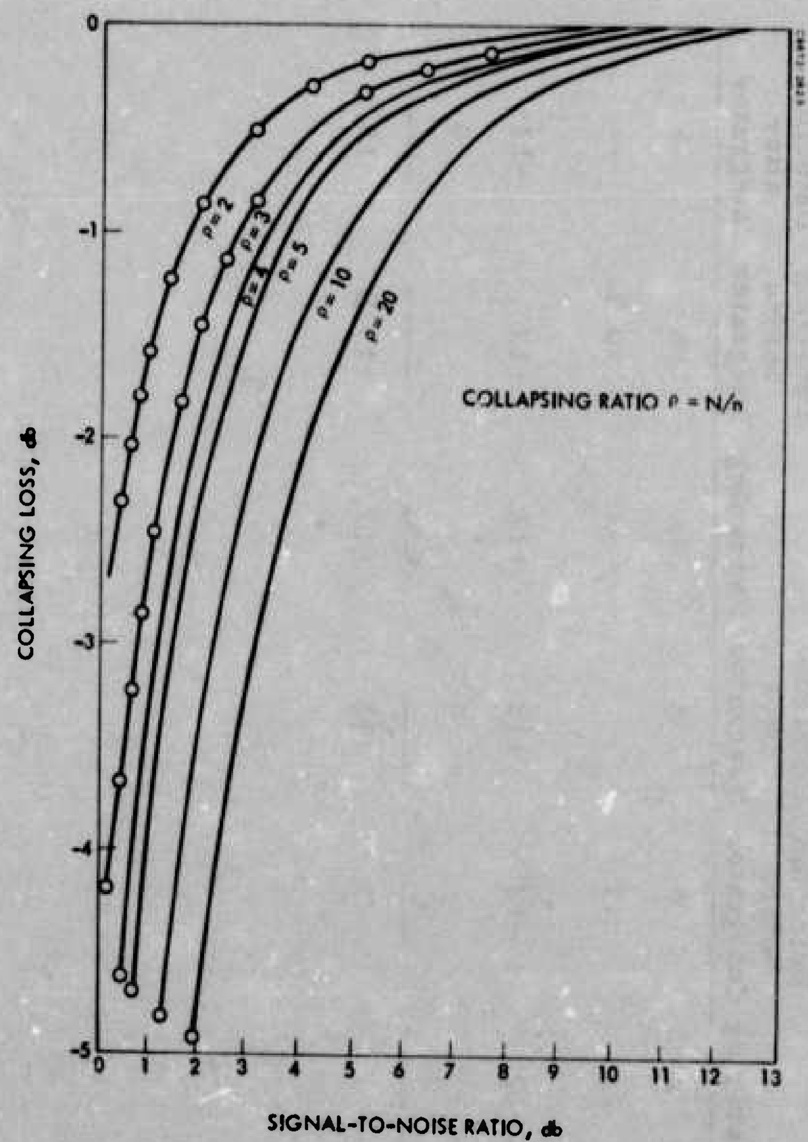


Figure 58. Loss in signal to noise ratio after peak detecting a sampled envelope of a sinusoidal signal plus narrow band gaussian noise.

that of the raw radar video at the input. However, it is not necessary to display a dynamic range much larger than that of the original video input for the following reasons: (1) The integrator's main purpose is to increase the signal strength of low SNR targets to detectable levels; any increase in high SNR target amplitudes is not necessary since further SNR improvement yields little improvement in detection performance. (2) The human eye is not capable of resolving more than about 16 shades of gray under the best of operational circumstances, which corresponds to a 48 db dynamic range. (3) Display devices typically are not capable of rendering even 16 shades of gray, but generally are limited to about 8-10, corresponding to a dynamic range of 24-30 db.

TABLE 31. COMPARISON OF SNR FOR THREE RANGE BIN COLLAPSING METHODS

	Small Target			Large Target		
	Averaging	Peak Detection before Integrator	Peak Detection after Integrator	Averaging	Peak Detection before Integrator	Peak Detection after Integrator
Input Target SNR	0	0	0	+6	+6	+6
Loss due to averaging or Peak Detection	-5	-5	-	-5	-0.5	--
Gain due to integration	+12	+12	+12	+12	+12	+12
Loss due to peak detection			0			0
Output SNR	+7	+7	+12	+13	+17.5	+18

For the above reasons, it is reasonable to truncate the video integrator output so that the truncated dynamic range is not significantly greater than the smallest of the three limiting factors mentioned, namely, the sensor output, the observer limit, and the display limit. In this way, the DSC memory size is minimized without being a limiting factor in gray shade rendition. Since the truncated output dynamic range is in general less than the full video integrator dynamic range, to prevent intensity errors on the display, it is necessary to sense any integrator output above the maximum displayed dynamic range and to be sure that the output gray shade level is set to the maximum intensity whenever such a condition occurs.

Two methods of video integrator output truncation are considered here, linear and logarithmic. In linear truncation, the desired output dynamic range is divided into a number of intensity levels by gray shade thresholds equally spaced in voltage. The number of bits required to represent a given dynamic range DR in db by equally spaced intervals is $L = \log_2 10^{DR/20}$. As discussed above, the desired output dynamic range is selected to match that of the smallest limiting factor (normally the sensor itself), and its lower limit is the integrator output level resulting from integrating the lowest input signal level from the sensor on M successive range sweeps, where M is the number of range sweeps per antenna beamwidth corresponding to each value of β. Since the lowest input signal level from the sensor is 1, the video integrator output corresponding to a constant input of this magnitude after M sweeps is $\sum_{i=0}^{M-1} \beta^i = (1 - \beta^M)/(1 - \beta)$. Thus the output dynamic range should have its lower limit at the value $(1 - \beta^M)/(1 - \beta)$, with thresholds at equally spaced intervals above this value for linear truncation. If β is small and/or M is large, we have $(1 - \beta^M/(1 - \beta) \approx 1/(1 - \beta) = 2^k$, so that in this case, the lower limit of the output dynamic range is found by ignoring the k least significant bits of the video integrator output. The only difference for log-arithmic truncation is that successive gray shade thresholds are set at

voltages whose ratio is $\sqrt{2} \approx 1.414$. The number of bits required to represent a given dynamic range DR by logarithmically spaced intervals,

i.e., $\sqrt{2}$ steps in intensity, is $L = \log_2 \left[2 \log_2 10^{DR/20} \right]$. Thus a given

dynamic range (>21 db) may be represented by fewer bits using logarithmic truncation than with linear truncation, or conversely, a given number of bits can represent a wider dynamic range with logarithmic truncation as opposed to linear truncation. Logarithmic truncation is of course somewhat more difficult to mechanize than linear truncation, but the potential memory size savings for large dynamic range requirements (>21 db) make it the preferred technique in such situations. Table 32 shows the dynamic range coverage attainable with various numbers of gray shade rendition bits using both the linear and logarithmic truncation techniques.

TABLE 32. DIGITAL VIDEO DYNAMIC RANGE

Number of Bits	Dynamic Range, db
Linear	
1	6
2	12
3	18
4	24
5	30
n	6n
Logarithmic	
1	6
2	12
3	24
4	48
5	96
n	$6 \times 2^{(n-1)}$

3.4 Image Processing

3.4.1 Introduction

Image processing can be generally defined as any operation deliberately performed on a video signal with the intent of improving its overall quality. Table 33 presents several techniques that could be used for modifying the video in an imaging system, briefly describes their operation and effect, their relative complexity and anticipated advantages, and presents conclusions regarding their applicability to video sensors commonly employed in airborne applications such as radar, IR, or TV. Techniques such as image motion compensation and geometric correction fall in the general category of spatial distortion reduction. Techniques such as inverse filtering, Wiener filtering, and recursive estimation are concerned with restoration of high spatial frequency information and improvement of the video signal to noise ratio. Finally, processing such as contrast enhancement, histogram equalization, and coefficient rooting is intended to bring out video information contained in an image as intensity modulation by operations is designed to make optimum use of the available video intensity dynamic range. As may be noted from Table 33, many of these processing techniques are rather complex from a hardware point of view, requiring large memories, possibly non-linear operation, and probably could not be implemented in real time, at least at present. Our conclusion is that histogram equalization is the technique which appears at present to yield the greatest benefits with the least cost in terms of mechanization complexity and the capability of real-time operation. We shall first describe the concept of histogram equalization in greater detail, and then present a description and discussion of a non-real-time computer simulation of histogram equalization performed in the laboratory.

3.4.2 The Concept of Histogram Equalization

The intensity histogram of a full frame of a typical natural image that has been linearly quantized is usually highly skewed toward the darker levels as in Figure 59. The intensity histogram of a frame is a graphic plot of the number of picture elements at each intensity level. In such images, detail in the darker regions is often not perceptible. One means of enhancing these types of images is a technique called histogram equalization in which the original histogram is rescaled so that the histogram of the enhanced image is scaled to one-half the number of levels of the original image. The scaling algorithm is developed as follows. The average value of the histogram levels is computed. Then starting at the lowest grey level of the original, the pixels in the quantization bands are combined until the sum is closest to the average. All of these pixels are then rescaled to the new first reconstruction level at the midpoint of the enhanced image forst quantization band. The process is repeated for higher value grey levels. If the number of reconstruction levels of the original image is large, it is possible to rescale the grey levels so that the enhanced image histogram is almost constant. It shou'd be noted that the number of reconstruction levels of the enhanced image must be less than the number of levels of the original image to provide the grey scale redistribution if all pixels in each quantization level are to be treated similarly. This results in a somewhat larger quantization. It is possible to perform the grey scale histogram equalization process with the same number of grey levels for the original and

TABLE 33. DIGITAL VIDEO COMPENSATION TECHNIQUES

Technique	General Description	Relative Complexity	Benefits	Recommendations
Image Motion Compensation	Eliminates effects of image motion during scan.	Requires two-dimensional convolution of image and a filter impulse response; full frame storage required.	Few or none.	Not applicable to most sensor video
Geometric Correction	Can compensate for aberrations in optical system.	Full frame storage required; difficult to implement in real time.	If optics are good, few advantages.	Growth potential
Inverse Filtering	Can compensate for high-frequency loss in system MTF.	Full frame storage required as well as transform operation; may be difficult to implement in real time.	Large potential improvement, but only in low-noise environment.	Complex
Wiener Filtering	Minimizes mean-squared error between image and reconstruction in a noisy environment.	Same comments apply as those for inverse filtering; also requires knowledge of the statistics of image and noise.	Large potential improvement, especially in a noise environment.	Complex
Recursive Estimation	Similar to Wiener filtering for some types of images.	Single-line storage required; easy to implement; requires image statistics; has been used only for images with exponential autocorrelation function.	Considerable improvement, particularly with noisy data.	Growth potential (requires statistical analysis of video)
Contrast Enhancement	Provides for reassignment of gray levels according to any desired function.	Easy to implement; may produce gray contouring; somewhat subjective.	Brings out detail in low-brightness areas but may saturate high-brightness areas.	Histogram equalization is recommended (special case)
Histogram Equalization	Reassigns gray levels for uniform distribution of intensities over entire image.	Easy to implement; may result in coarser gray quantization.	Enhances detail in predominant areas of image.	Recommended
Edge Crispening and Detection	Increases sharpness of image and may aid in detection.	Moderately easy to implement; some susceptibility to noise.	Accentuates boundaries of object; brings out details.	Recommended (growth potential)
Coefficient Rooting	Energy redistribution in transform domain in order to use image dynamic range to better advantage.	Full frame storage required as well as transform and nonlinear operations; could be quite slow.	Makes better use of image dynamic range.	Complex
Generalized Cepstrum	Logarithmic transform operation provides better dynamic range and edge enhancement.	Full frame storage required as well as transform and nonlinear operations; slow.	Same remark applies as that for coefficient rooting; also, some inherent edge enhancement can be obtained.	Complex
Noise Cleaning	Removes isolated noisy image elements	Easy to implement, but may take too much time for results obtained.	Little improvement; reduces noise at isolated points.	Not applicable in general
Local Automatic Brightness Control	Adds d-c bias to local areas of image or subtracts it from these areas.	Easy to implement and not unduly complex.	Good if used with video gain control (AGC); prevents saturation.	Recommended

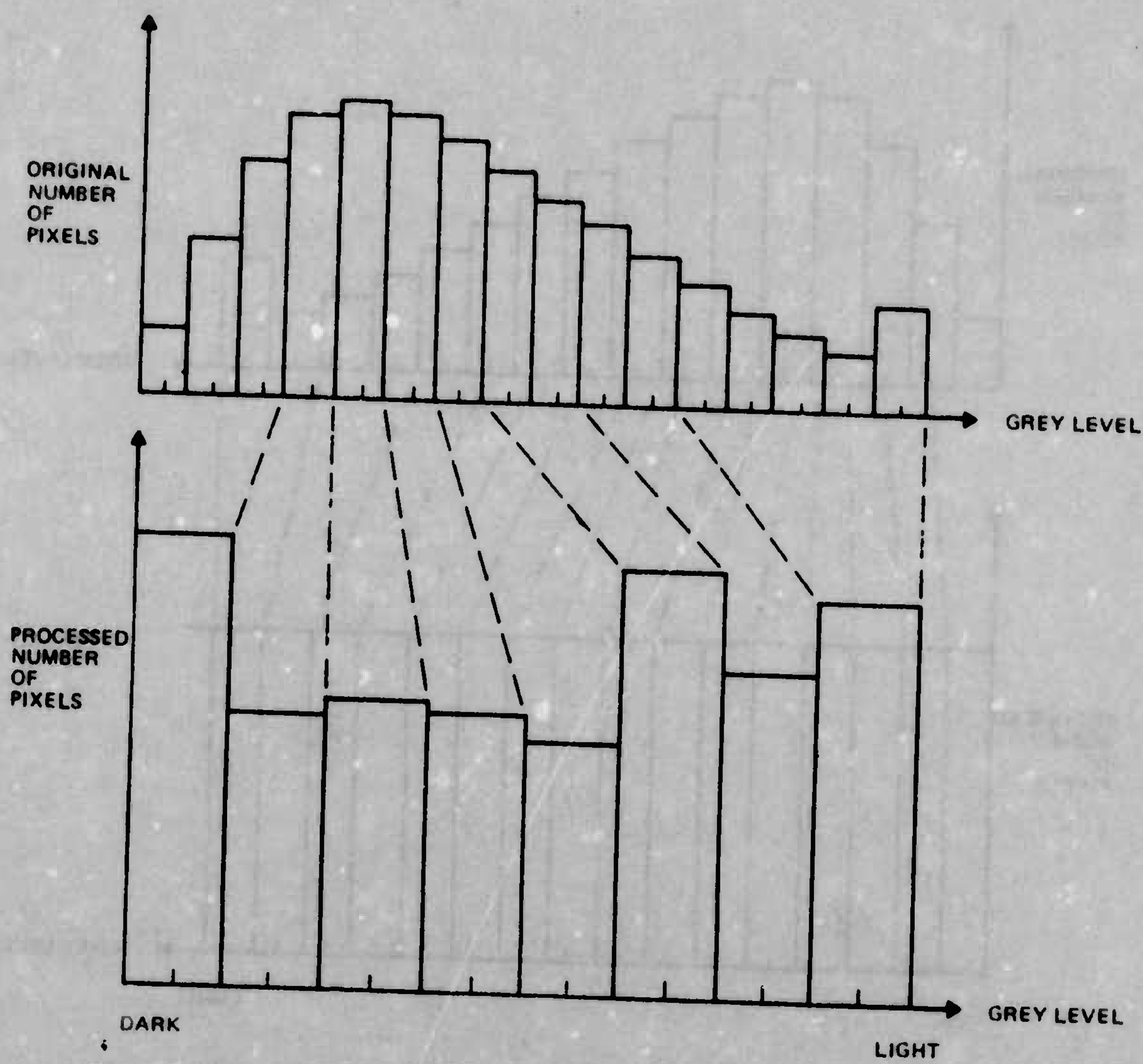


Figure 59. Grey level histogram equalization with unequal numbers of quantization levels.

enhanced image by randomly redistributing pixels as indicated in Figure 60. This processing technique was simulated on the basis of its expected benefit in relation to cost and time requirements as well as its relative ease of mechanization.

One of the disadvantages of full frame histogram equalization as discussed above is that this process tends to be somewhat insensitive to localized intensity variations within the frame. This led to the development of one-dimensional band histogram equalization, which is histogram equalization using a fractional frame at a time, i.e., using only N lines of a total of M per frame in computing the current intensity histogram. Experimentation with this method yielded the conclusion that it was indeed more sensitive to local brightness variations than the full frame version, thereby yielding better contrast over the full frame area, while bringing out details which

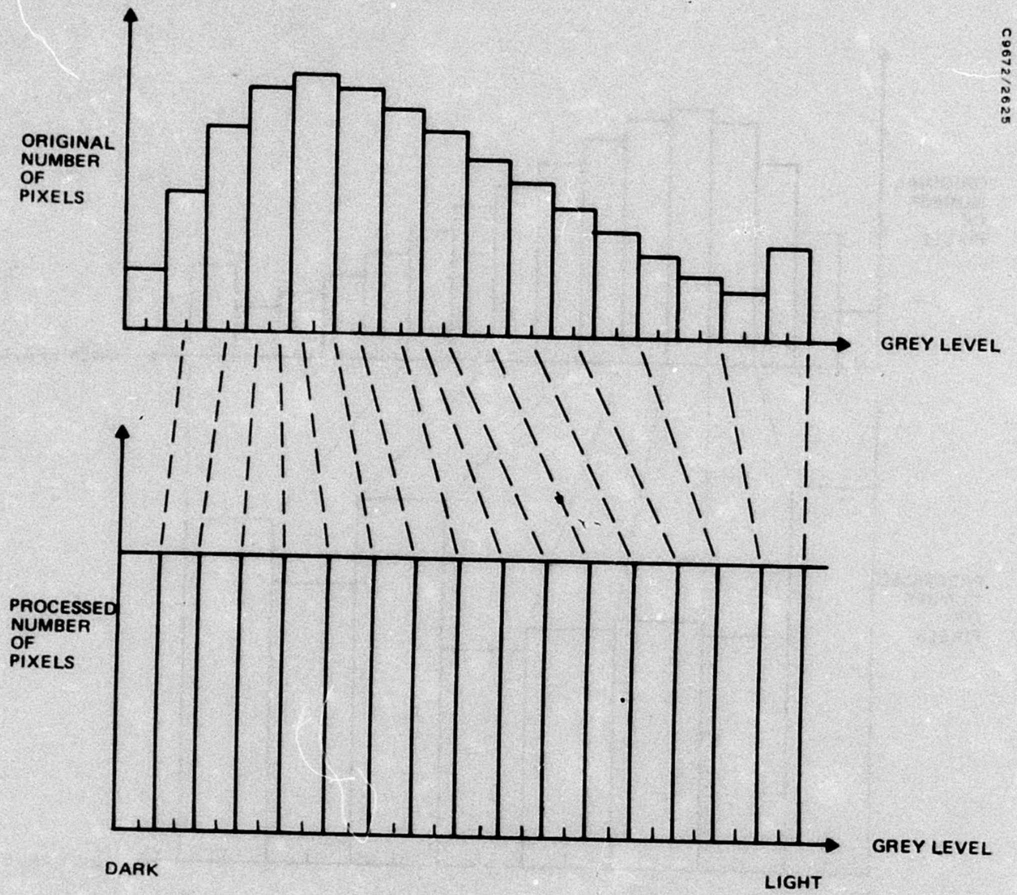


Figure 60. Grey level histogram equalization with equal numbers of quantization levels.

in the original had been saturated or washed out. This method also requires less memory but more logic and bookkeeping operations than the full frame technique.

The logical extension of one-dimensional band histogram equalization is to two-dimensional box histogram equalization. The object again is to increase sensitivity to localized brightness variations while preserving the detail enhancement properties of these techniques. Mechanization of this technique, however, requires a large amount of bookkeeping, and in addition, its operation is dependent on the size of the box to a greater degree than in the case of average brightness control. The fundamental reason for this is that for a small box size, for example nine by nine, and 64 grey levels, the resulting grey level histogram within the box tends to have singular behavior, resulting in a somewhat meaningless grey level redistribution. Thus two-dimensional histogram equalization is fundamentally limited in terms of a lower limit on the box size, and for larger dimensions, the bookkeeping and storage requirements make this technique less attractive than it first appears, when compared with some of the other methods presented previously. However, further experimentation should be done on all of these variations before a final judgement is made.

3.4.3 Laboratory Simulation of Histogram Equalization

Figure 61 is a block diagram of the laboratory equipment used to simulate the histogram equalization processing. The original image transparency is mounted in the flying spot scanner (FSS). The position and blanking of the FSS beam are controlled by the digital computer program through the D/A converters on the special interface unit (SIU). The FSS beam is stepped from one pixel position to the next, and at each step the output of the FSS photomultiplier tube (PMT), representing the video intensity of that pixel, is A/D converter and stored in the computer as part of the original image array. The entire original image and any intermediate versions generated during processing are stored on the magnetic disc associated with the Σ5 to conserve memory space within the computer itself. The computer software then carried out the algorithms described above, either for full frame or one or two dimensional partial frame histogram equalization. This, of course, involves finding the original image histogram, reassigning the gray level thresholds, and then modifying the original image intensity pattern according to the new (equalized) gray level thresholds. The output of the computer is recorded on film as follows. The X and Y position of the electron beam of a Tektronix 536 scope is controlled by the computer through the D/A converters

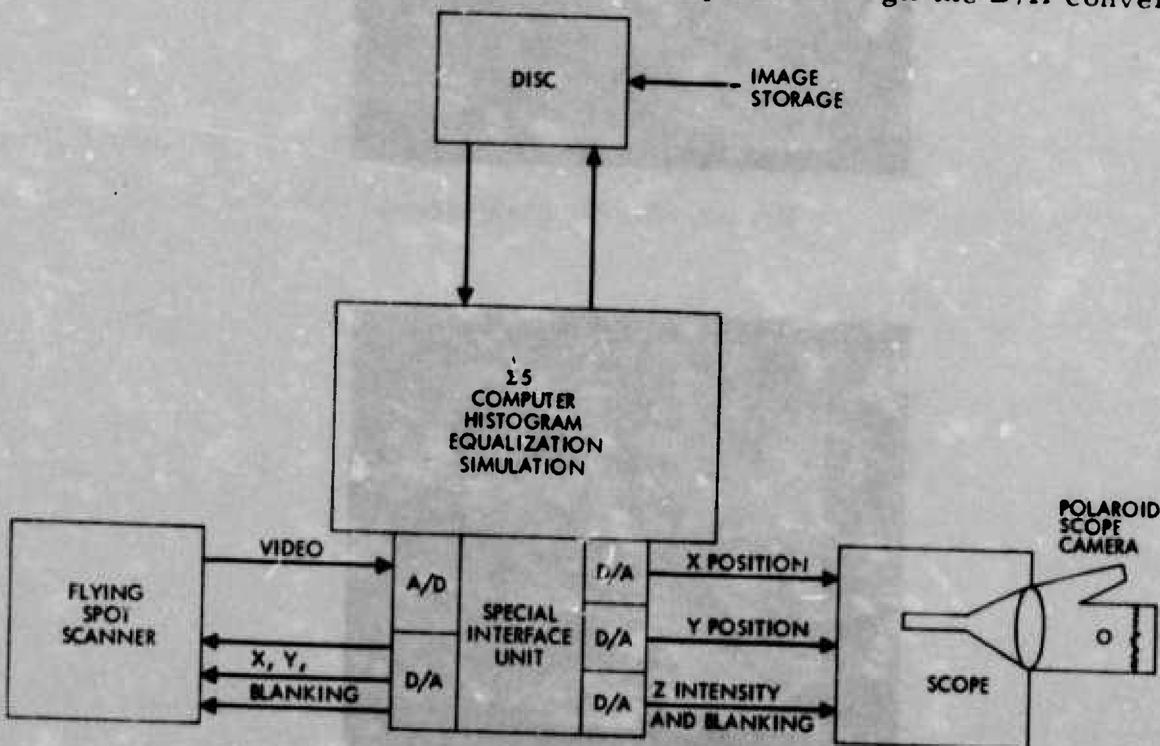


Figure 61. Lab simulation block diagram.

of the SIU, just as on input. Another D/A converter is used to control the intensity and blanking of the scope electron beam, which scans out the entire image area as on input and in the process exposes the film in a Polaroid scope camera.

Figure 62 is a scope photograph of F-111 radar imagery which has been digitized to a resolution of 256 x 256 elements with 6 bit intensity quantization, through the FSS input. It was then output directly to the scope without processing, so this represents the original unprocessed imagery. Figure 63 shows the results of the full frame histogram equalization processing, with the same resolution and number of gray shade rendition bits as the original in Figure 62. Note that the light areas, which statistically account for a relatively small area of the original, have been greatly accentuated in Figure 63, resulting in much greater apparent contrast. However, one may also note that some of the mid-gray areas appear to be somewhat washed out, especially in the upper half of the image, as though there were to much intensity correction. Figure 64 shows the same image after one-dimensional

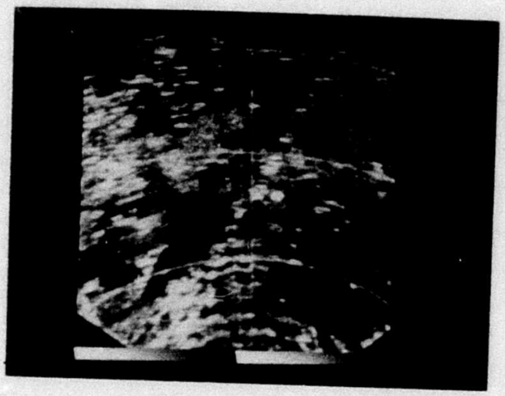


Figure 62. Original scene.

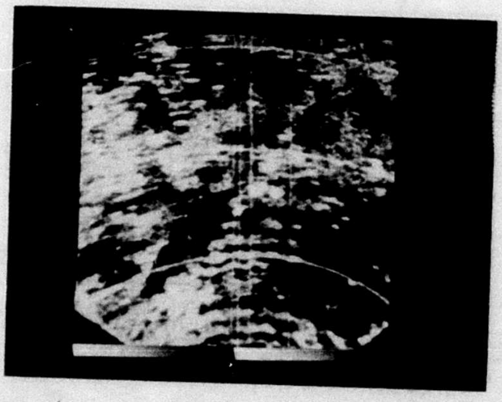


Figure 63. Full frame histogram equalization.

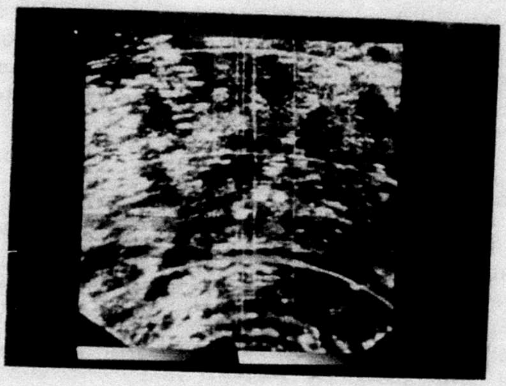


Figure 64. Local histogram equalization.

band histogram equalization over 32 lines at a time. The light areas have still been accentuated relative to the original, but the mid-grays are better preserved than in Figure 63. This can be attributed to the greater sensitivity of the band equalization technique to local variations in the statistics of the intensity distribution than the full frame equalization technique, which assigns the new gray level thresholds once and for all on the basis of the distribution of video intensities over the whole frame.

These results are inconclusive regarding the suitability of defining special processing modules for the MMSDS system. Further evaluation, simulation and ideally the development of a breadboard should be undertaken before committing any of the processing techniques to a field application. However, in the module design section of this report, the functional mechanization of a histogram equalization module for radar is described.

3.5 Memory Considerations

The most important design decisions required in the development of a digital display system involve the digital memory. These include not only the considerations which determine the type of digital memory, but also the formatting of the data stored for ease of read-out and display. A memory can be formatted and read out in one of two ways. The first is to store the sensor video sequentially in the memory as it is received from the sensor and achieve the various formats by formatting the display sweeps upon readout. This approach uses simple memory addressing logic, but requires high power linear deflection amplifiers in the display indicator. The alternate way is to always read the memory out in a horizontal television raster format thereby requiring complex memory load address generation but permitting the use of a lower power resonant deflection TV indicator. It also provides for simple recording of the video and establishes a standardized interface such as EIA standards RS 170 and RS 343. A standard orthogonal raster readout will also probably be required for future matrix addressable flat panel display techniques.

A summary of the basic formats to be handled in the digital scan converter are shown in Table 34. Also tabulated is the function of the digital scan converter for each of these formats; that is rate conversion (slow scan to fast scan) or format conversion (PPI to TV). Obviously the freeze mode is provided for all formats. Some of the unique characteristics of these various modes will now be discussed.

3.5.1 Coordinate Conversion

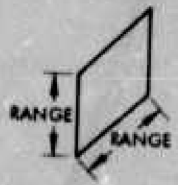
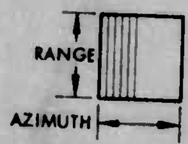
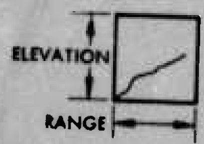
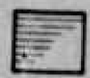
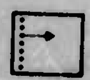
In the B-scan, E-scan, FLIR, or TV modes, there is no difference in image quality or display appearance for either a TV raster or linear display format since both represent an orthogonal transformation or mapping of the sensor data to the display surface. However, in the PPI modes, there is a major difference in the transformation of the data from the radar to the display surface as a function of whether a TV raster or PPI format is generated on the display. Whether this results in a significant difference in image quality or display appearance depends on the radar resolution characteristics and the DSC spatial quantization. The TV raster display presentation is characterized by constant Δ_X and Δ_Y resolution elements, where Δ_X is the display width divided by the number of horizontal samples and Δ_Y is the display height divided by the number of television scan lines.

The linear sweep PPI format provides constant range and angular resolution elements, Δ_R and Δ_θ, where Δ_R is the range scale divided by the number of range samples and Δ_θ is the azimuth scan width divided by the number of azimuth samples. Radar resolution is defined in terms of the pulse width in range and the antenna beamwidth in angle and therefore corresponds to the linear sweep format resolution parameters. The TV raster resolution parameters must, therefore, be converted to equivalent radar resolution elements in order to compare the performance of the two systems.

Basic assumptions for the analysis were: 1) a square display and 2) an array of m x n memory bins, or elements, on the display (x and y axes, respectively). For the sake of generality, the display is considered to be a 180 degrees offset sector plan position indicator (PPI) with 0.0 degree azimuth coincident with the +X axis. To obtain consistency of results, it was assumed that the azimuth and range uncertainities are centered about a bin, since the address of an element anywhere within a bin will cause a response throughout the bin. The resulting geometry is illustrated in Figure 65. Quantization of range and azimuth angle is performed prior to the transformation. Given an element at arbitrary range, R, (inches on display) and azimuth θ, the display range and azimuth resolution is given by the following expressions:

$$\Delta R = \begin{cases} \dfrac{\sec\theta}{m}, & 0 \le \theta \le \theta_{CRIT.}{}^{R} \\ \dfrac{\csc\theta}{n}, & \theta_{CRIT.}{}^{R} \le \theta \le \pi - \theta_{CRIT.}{}^{R} \end{cases} \qquad (4\text{-}1)$$

TABLE 34. SUMMARY OF BASIC DISPLAY FORMATS

SENSOR MODE	FORMAT	DSC FUNCTION	
		TV MONITOR	LINEAR MONITOR
RADAR			
PPI		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
SIDELOOKING		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
B-SCAN		COORDINATE CONVERSION AND RATE CONVERSION	RATE CONVERSION ONLY
E-SCAN		RATE CONVERSION ONLY	
FLIR			
DISCOID (TV RASTER)		REQUIRED FOR FREEZE ONLY	
SCANNED MULTI-DETECTOR ARRAY		REQUIRED FOR FREEZE AND COORDINATE CONVERSION	
TELEVISION			
		REQUIRED FOR FREEZE ONLY	

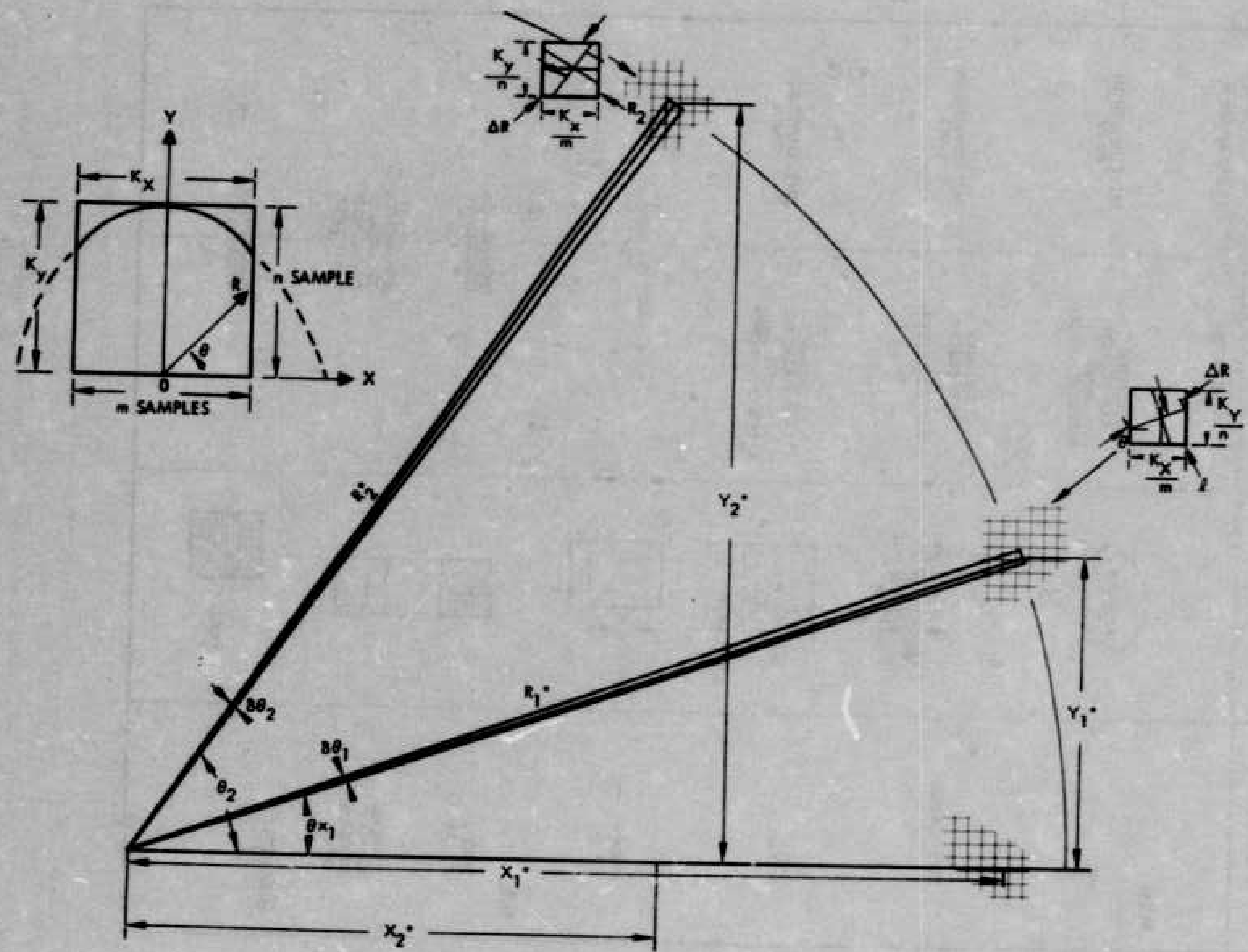


Figure 65. Display geometry: PPI on a digital rectangular display.

$$\theta_{CRIT.}{}^{R} = \arc\tan \frac{m}{n}$$

$$\Delta\theta = \begin{cases} 2 \arctan \dfrac{1}{2n \frac{R}{K} \cos\theta} & \theta \leq \theta \leq \theta_{CRIT.}{}^{AZ} \\ \\ 2 \arctan \dfrac{1}{2m \frac{R}{K} \sin\theta} & \theta_{CRIT.}{}^{AZ} \leq \theta \leq \pi - \theta_{CRIT.}{}^{AZ} \end{cases} \qquad (4\text{-}2)$$

$$\theta_{CRIT.}{}^{AZ} = \frac{\pi}{2} - \theta_{CRIT.}{}^{R} = \arctan \frac{n}{m}$$

The azimuth resolution at $\theta = 0$ degrees as a function of the number of vertical samples, n, for various R/K ratios is plotted in Figure 66. For example, to provide a resolution element of 3 degrees at a minimum of 10-percent range on the display requires approximately 192 samples or resolution elements across the display.

The locus of equal-angle resolution elements is a rectangle about the vertex of the PPI format as shown in Figure 67. By plotting the locus of points representing the Nyquist sampling resolution, and computing the percentage of total display area that provides greater resolution than Nyquist sampling, another performance criteria can be established to determine the number of samples required for a specific system. This is plotted in Figure 68 as a function of the ratio of display horizontal samples m (assuming m = n) to the number of Nyquist samples in a scan width for various scan widths. For example, to maintain 90 percent of the display area in excess of the Nyquist resolution criteria for a sector scan of 120 degrees would require a minimum of twice as many display samples as Nyquist samples.

The range and azimuth resolutions were also computed for a typical PPI display format with a 120-degree sector scan and a 256- by 256-resolution element display. The results are shown in Figures 69 and 70.

3.6 Digital to Analog Conversion

The digital video, once stored in the memory, does not vary and is a linear representation of the video received element by element from the sensor (assuming linear A/D conversion). Since cathode ray tubes and the human visual system are more or less operationally limited to approximately 11 shades of gray, it is impractical and inefficient to store more than 4 bits. In fact, 3 bits is sufficient for many cases and indeed even 2 bits may be sufficient for most detection purposes. The important consideration is the rendition of

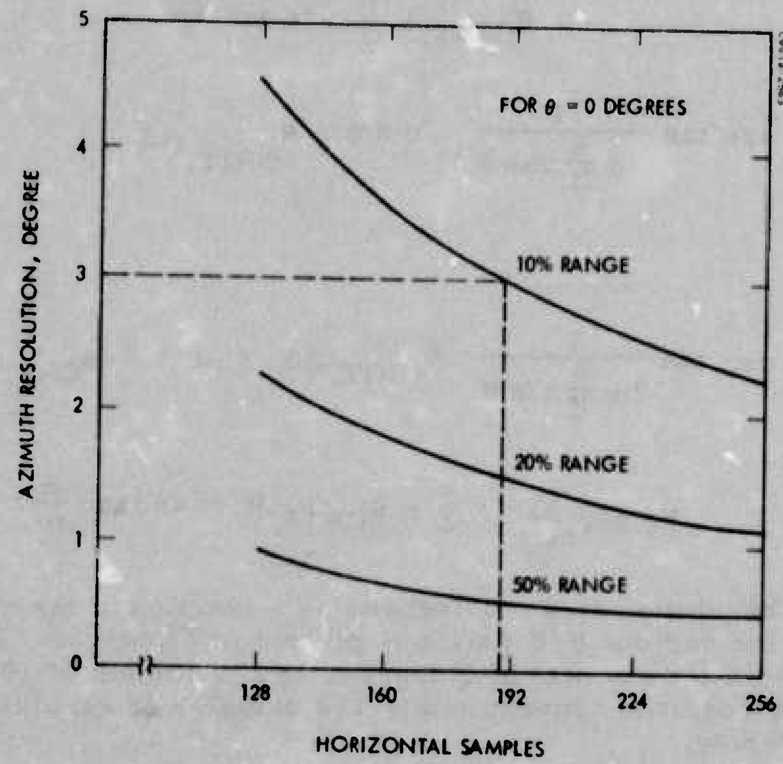


Figure 66. Azimuth resolution versus number of vertical samples for θ = 0 degrees.

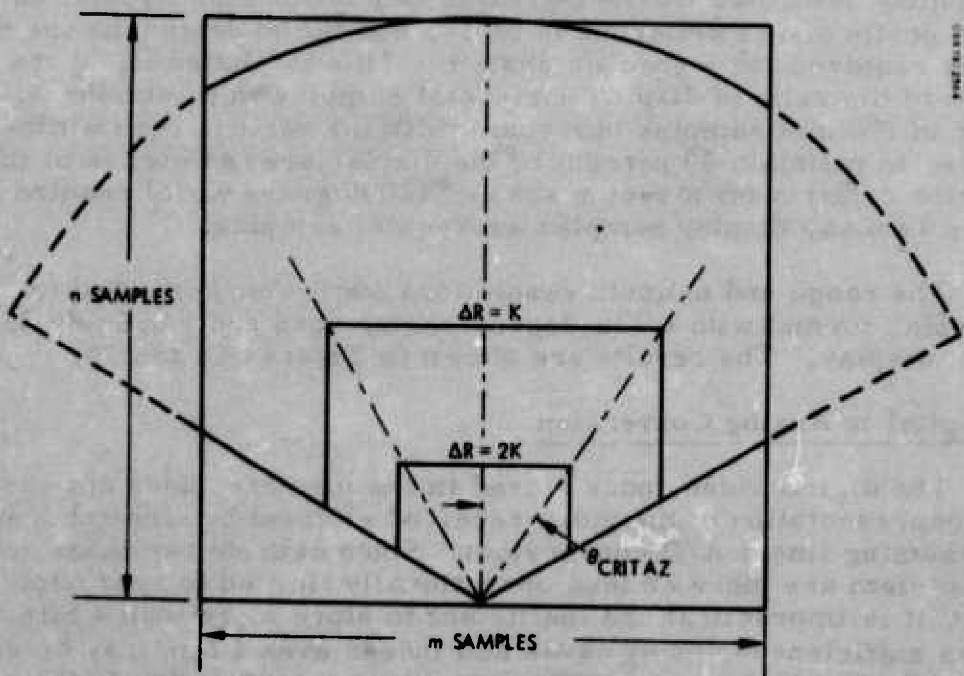


Figure 67. Locus of equal-angle resolution elements.

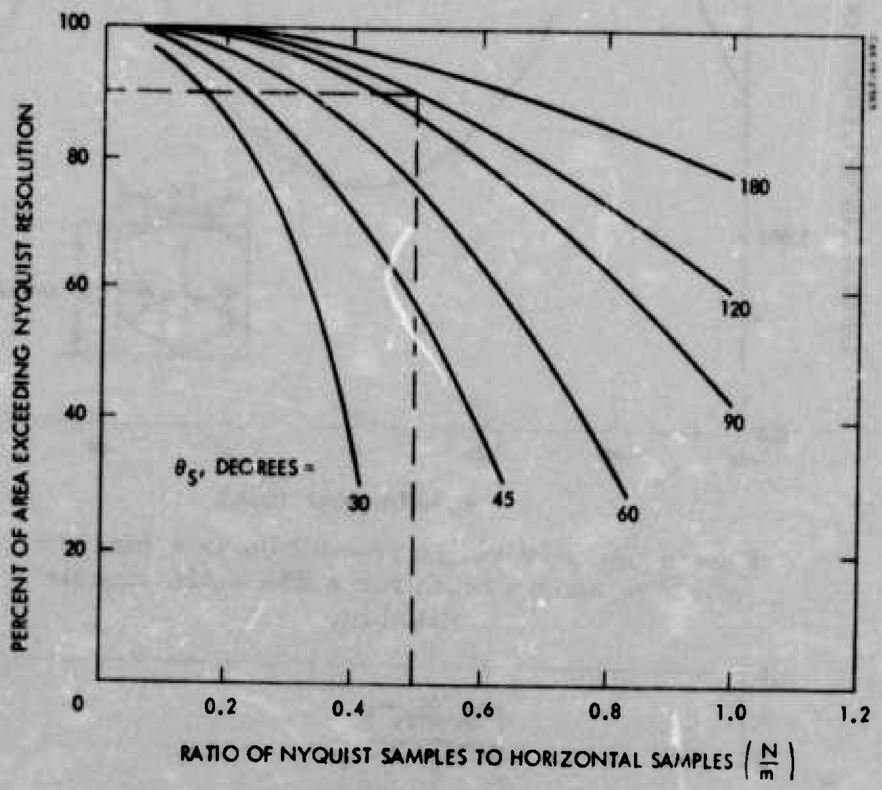


Figure 68. Percent of display area that exceeds Nyquist azimuth resolution as a function of ratio of Nyquist samples to horizontal samples for various scan widths.

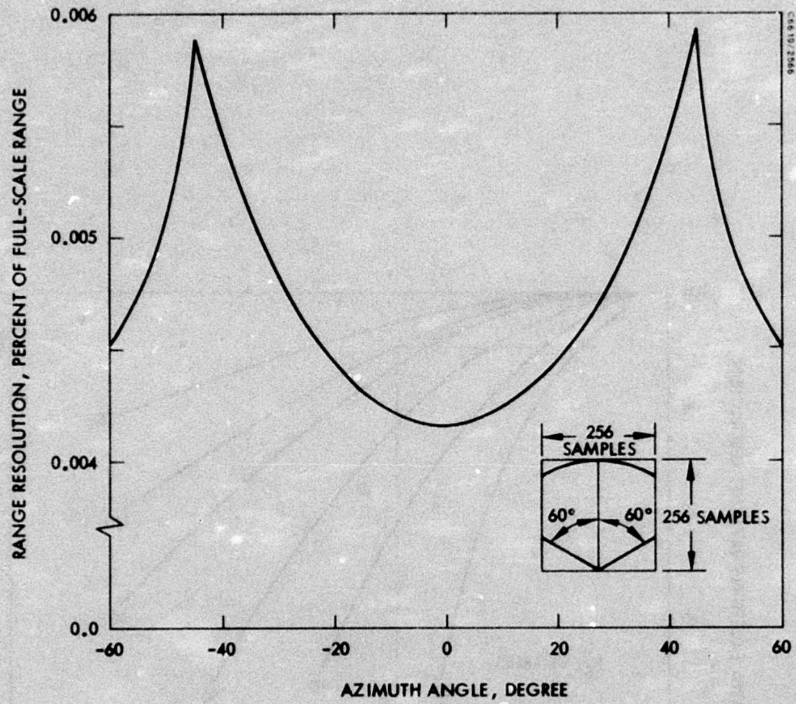


Figure 69. PPI range resolution as a function of range and azimuth for a 256 x 256 sample display.

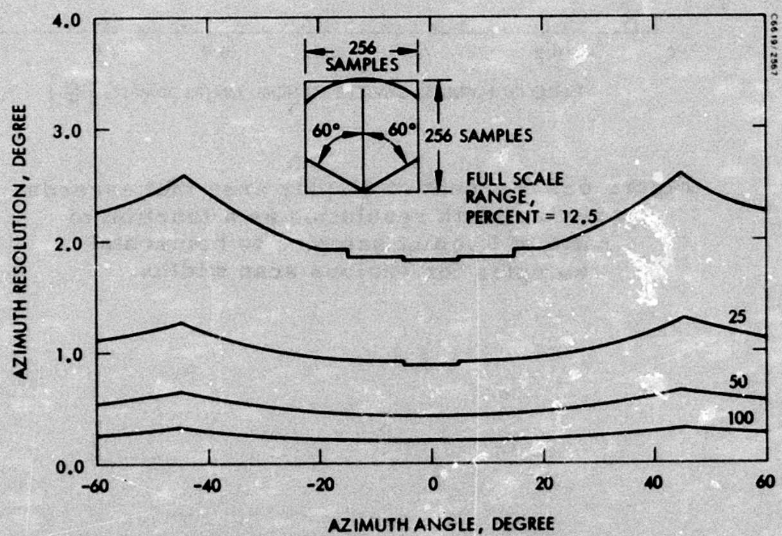


Figure 70. PPI azimuth resolution as a function of range and azimuth for a 256 x 256 sample display.

the discrete levels stored to maximize the number of discernible gray shade levels displayed. With a totally linear display system, the 4 bits are linearly D/A converted, and the resultant analog voltage drives the display CRT in the manner shown in Figure 71. (Assuming operation in the linear region of the CRT transfer curve.) Since the dynamic range of a linear 4-bit system is only 15:1, only about 6 shades of gray can be displayed at a time. This is because each successive higher gray shade must be at least 1.4 times brighter than the next lowest to be easily discriminable. (1.4 is a nominal value, actually the required contrast is a function of resolution, brightness level, and other factors.) With only 6 discernible shades of gray, optimum utilization of the 16 stored energy levels is not being achieved. Also, the gray scale capability of the observer and display is not used. To maximize the information content, each successive gray scale level should be displayed with 1.4 times the brightness of the previous one.

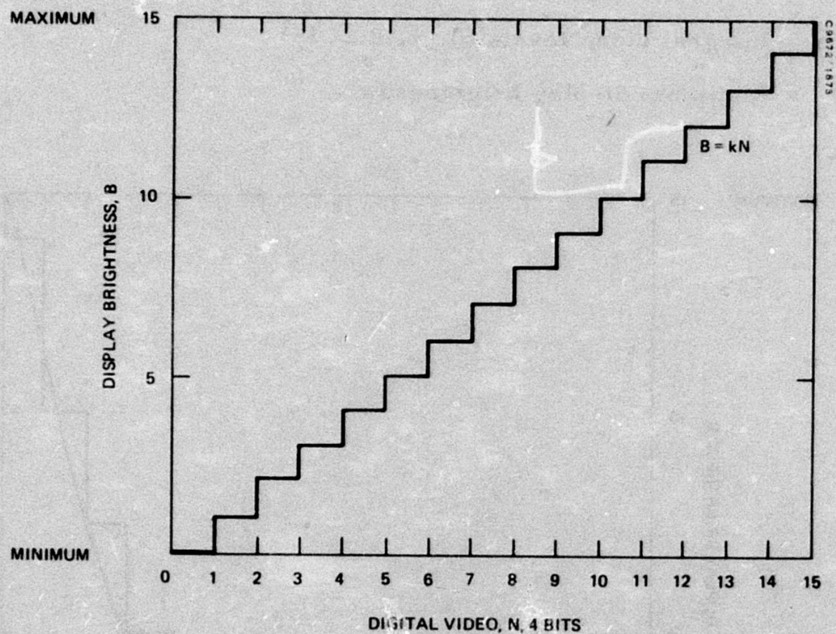


Figure 71. Sample of a linear gamma.

To provide the required transfer function (gamma) to convert from the elemental stored energy levels in the digital scan converter memory to a maximum number of discriminable gray shades on the CRT, a non-linear transfer network is required. This can be either digital logic prior to D/A conversion or analog circuitry afterward. The digital mechanization is preferred, because digital circuitry is less susceptible to drift, requires no adjustment, and hence requires minimum maintenance and provides a lower cost of ownership.

The network must be designed to provide an output brightness level increase of 1.4 for each successive brightness level. For the optimum design, the actual (or predicted) transfer curve of the CRT must be considered. The desired brightness curve is shown in Figure 72. The transfer function of the digital network is:

$$B = K(\sqrt{2})^n + B_o$$

where

B = display brightness

K = Mechanization constant

n = Integral video levels (0, 1, 2... 15)

B_o = Minimum display brightness.

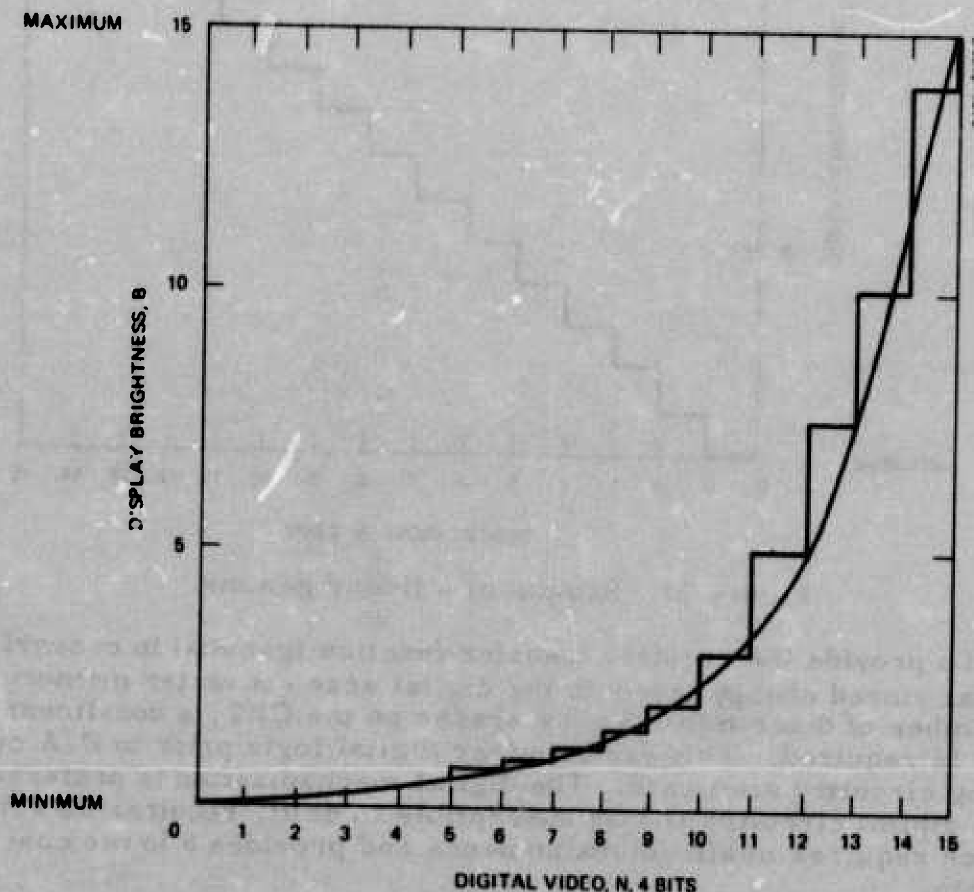


Figure 72. Sample of a logarithmic gamma.

3.7 Video Filtering

Digital scan converter systems have been qualitatively evaluated, during numerous flight test and laboratory demonstrations. One rather frequent objection to the display is that of the sharp well defined digital samples. In analog systems, the video appears smoother and continuous. Of course, this problem could be alleviated by providing more digital samples than necessary to meet the information transfer requirements. Such a solution, however, would result in a more costly system. Another solution is to provide interpolated samples between the actual samples. However, this has the same affect as the less complex technique of using output smoothing filters placed after the D/A converter. In their simplest form, they consist of a simple rolloff network. Figure 73 indicates the bandpass characteristics of 4 such filters (w1 through w4) evaluated with a laboratory digital scan converter. Photographs of the displays with the w1 and w4 filters are shown in Figures 74 and 75. The filter 3 db points are referenced to the frequency content of the stored, and displayed, digital video. w is the band limit of the stored video (2 digital samples per cycle). The tradeoff in the application of the simple filters is to minimize rolloff of the desired video ($F < w$) while attenuating the higher frequency noise components ($F > w$). The higher frequency noise components show themselves on the display as the sharp transitions between the samples. These high frequency components are not present in the stored information and hence can be considered sources of noise. The conclusions with regard to the simple rolloff filters, is that a cutoff filter with a 2w band pass offers the best high frequency noise attenuation while minimizing signal rolloff.

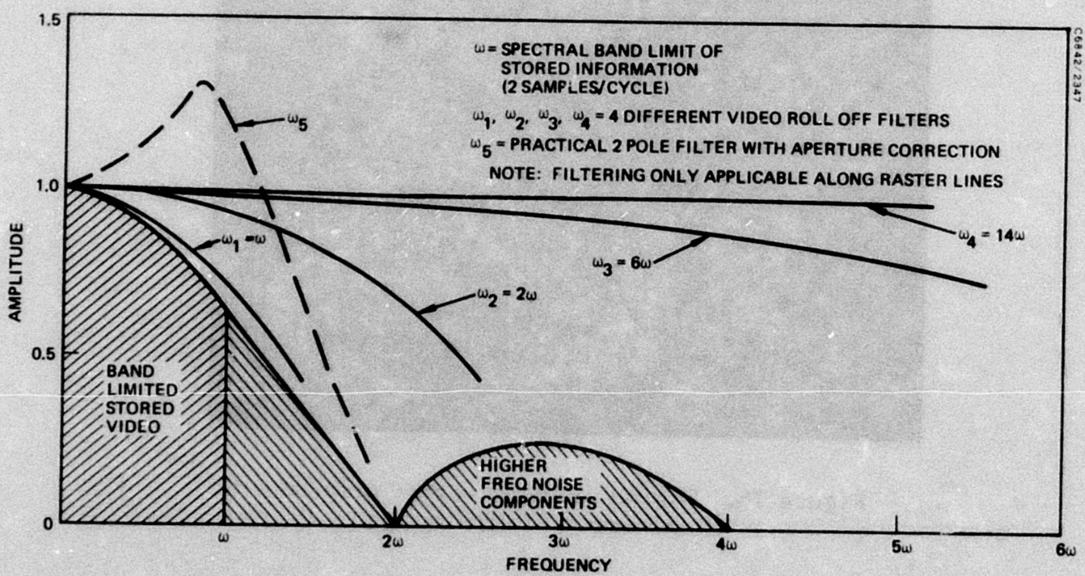


Figure 73. Bandpass characteristics of alternate video filters.

Figure 74. Digital scan converter display with maximum rolloff filter.

Figure 75. Digital scan converter display with minimum rolloff filter.

In addition to the simple rolloff filters, a complex 2 pole high rolloff filter was designed and evaluated. This filter, w_5, essentially provides peaking to restore the stored video rolloff due to sampling and effectively attenuates the higher frequency noise components. It represents a more complex design and is more susceptible to ringing. It does, however, work as an aperture corrector to increase signal modulation. This effect is obvious in the photograph (Figure 76) of the PPI digital scan converter display utilizing this filter. Also, it should be noted that the sampling theory states that such a reconstruction filter is required when sampling of the video is achieved at or near the Nyquist limits (N = 1/2 F). As such, a filter of this type is required in the Modular Multisensor Display System.

Figure 76. Digital scan converter display with complex aperture corrector filter.

3.8 Electro-Optical Sensor Considerations

Most electro-optical sensor video is available in a standard TV format, either directly from the sensor or having been scan converted within the sensor. Thus, the main function of the DSC for such sensors is to provide a freeze capability while minimizing further loss of MTF due to sampling. We shall discuss four types of EO sensors: (1) TV, (2) Forward Looking Infrared (FLIR), (3) EO Line Scanner (EOLS), and (4) Infrared Search and Track (IRST).

3.8.1 TV

Included in the airborne TV EO sensor family are a number of LLLTV systems, TISEO, TV Guided Weapons (Walleye, Maverick, Condor, etc.) and TV sighting units. All of these TV sensor systems are generally compatible with either the EIA RS-170 or EIA RS-343-A standards for monochrome TV.

Guided weapons such as Maverick use the 525 line TV. Walleye also employs the 525 line TV in compliance with MIL-T-81624. The 525 line TV raster is in wide use now, but the Modular Multi Sensor Display System should also provide 875 line as well as growth to 1023 line TV capability for future high resolution systems.

A 1:1 aspect ratio is quite typical for guided weapon systems, and a change in timing and control mechanization from that required for 3:4 aspect ratio TV format must be made to display missile TV. In the display freeze mode the DSC is required to store the desired video frame or field for display refresh.

The desirability in certain situations of a field freeze only, as opposed to a full frame freeze, stems from video smear considerations. Imagine a TV sensor with 20° square FOV in an aircraft traveling with a velocity of 1000 ft/sec at an altitude of 1000 ft. When the TV camera looks down beneath the aircraft, the 20° FOV covers about 350 feet on the ground 1000 feet below. If the raster has 525 lines, of which 240 per field are active, this is a spacing of about 18 inches on the ground between successive raster lines of a field. The next field is scanned 16 msec later, but during this time the sensor has moved 16 msec x 1000 ft/sec = 16 ft, so the following field is displaced $\frac{16\ \text{ft}}{18\ \text{in/line}} \approx 11$ raster lines from where it should be. Thus the interlaced video is displaced from its proper position, which produces image breakup and distortion. If only one field at a time is scanned and repeated twice per frame in the freeze mode, this image breakup is avoided, at the cost of some resolution, although the full 525 line resolution would probably not be available anyway under the conditions of image distortion described above.

Of course, with different geometries and dynamics, it is necessary to provide full frame freeze as well. Thus it is recommended that both capabilities be provided in the MMSDS system.

Table 35 gives the relevant parameters for the standard types of TV systems. To provide a full frame freeze capability without loss of resolution, the DSC should have a number of vertical samples equal to the number of active lines per frame as given in Table 35. In the horizontal direction, we want to provide isotropic resolution on the display, so the number of horizontal samples whould be equal to the number of active lines, if the aspect ratio is 1:1, and 1.33 times the number of active lines, if the aspect ratio is 4:3. Thus, for a 1:1 aspect ratio of 525 line TV, we should take 480 samples per line. With an active line time of 56.49 sec, this is $\frac{56.49}{480} = 0.11768$ sec/sample, corresponding to a sampling rate of $\frac{480}{56.49} = 8.50$ MHz. The analogous figures for the other types of TV systems are included in Table 35.

TABLE 35. HIGH RESOLUTION TV SYSTEM PARAMETERS

Lines/ Frame	Active Lines	f_h (1), KHz	t_{h_a} (2), μsec	Sampling Rate for Isotropic Resolution, MHz 4:3 Aspect	Sampling Rate for Isotropic Resolution, MHz 1:1 Aspect	Video Bandwidth, MHz 4:3 Aspect	Video Bandwidth, MHz 1:1 Aspect
525	480	15.75	56.49	11.33	8.50	5.67	4.25
675	624	20.25	42.38	19.63	14.72	9.82	7.36
729	674	21.07	38.72	23.21	17.41	11.61	8.7
875	809	26.25	31.09	14.69	26.02	17.35	13.01
945	874	28.35	28.27	41.22	30.92	20.61	15.46
1023	946	30.69	25.58	49.31	36.98	24.66	18.49

(1) f_h = Horizontal line frequency

(2) t_{h_a} = Active horizontal line time

Vertical Blanking = 1250 μsec nominal

Horizontal Blanking = 7 μsec nominal

Most TV sensors have a video dynamic range between 30 and 35 db, which requires 5 or 6 bits of resolution in the DSC input A/D converter and 4 bits per pixel if a logarithmic gray shade representation is used. Thus a DSC memory with full frame freeze capability for a 525 line 4:3 aspect ratio TV sensor would have 480 x 640 x 4 = 1,228,800 bits of memory, which is 3 times as large as that required for the typical radar system, namely 392K bits, assuming a radar memory configuration of 512 x 256 x 3. It is beyond the scope of this study to determine whether the importance of providing a full frame freeze mode justifies the cost of the much larger memory. Should this cost not be justifiable, there are two alternatives for compromise, either or both of which can be provided due to the flexibility in the design of the DSC. This flexibility comes from the programmable controller and modular memory. Both alternatives are based on the assumption that the memory size is confined to that required for the radar display functions. The first alternative is to provide a freeze mode covering the full FOV, but with reduced resolution. This could be achieved by, for example, a 512 x 256 x 3 reorganization of a 392K bit memory, resulting in full coverage of the FOV with reduced resolution and a reduced video dynamic range capability. Further study in this area would be required to determine the optimum allocation of resolution among the various display dimensions. The second alternative is to provide full sensor resolution, but with a reduced field of view. Under this alternative, about 1/3 of the total field of view could be displayed at one time (with the example indicated). Study in this area is required to determine the shape and possibly the placement of the sector of the FOV to be displayed.

3.8.2 FLIR

The typical imaging FLIR sensor consists of a vertical array of detectors scanned horizontally at a 60 Hz rate. Vertical interlace is achieved by moving the array vertically a distance equivalent to half the detector spacing on alternate fields. Because the FLIR scanning technique is not compatible with the TV scan sequence, some form of scan conversion is required. In most existing FLIR sensors, the scan conversion is performed in one of two ways. One technique utilizes an array of LEDs, each modulated by the video from a single detector. The LED array is scanned in synchronism with the detector array and is viewed with a closed circuit TV camera. The resultant video is TV compatible. The other way is to electronically multiplex the video from the IR detector array into one video signal. This signal modulates the write beam of an analog scan converter. The write beam of the analog scan converter is deflected in sync with the scanner IR array. Read out of the analog scan converter is achieved in a television format. Thus digital scan conversion is not required to convert the FLIR format, but to provide a freeze capability.

The NARBS FLIR is an advanced FLIR system under development by Hughes that is fully compatible with standard 525 line TV. This type of FLIR sensor requires no scan conversion, and the DSC would only be used to provide the freeze mode. The requirements for the freezing of a frame or field of FLIR video in a television format follow the same criteria as those for a television sensor previously discussed. The size of memory and frozen area of the field of view depends on the quality of freeze display desired. Laboratory studies are recommended to define the optimum means of providing such a freeze capability.

3.8.3 EOLS

Electro Optical Line Scan (EOLS) system, as exemplified by the AN/AAS-18A Equipment, typically generates high resolution infrared across-track video returns that are presented on the face of a recording CRT for optical imaging onto a moving film strip. This same line trace video can also be fed to a DSC to build up a passing scene data field in DSC memory. Line scan data is loaded into the DSC by means of appropriate data formatting, A/D conversion, write address control, and timing for the line scan data conversion mode. The DSC is read out in a conventional TV horizontal raster scan format. The 875 line TV raster would be a good choice for display of EOLS data to provide maximum along the track coverage.

The number of horizontal samples in the DSC for this type of sensor is determined from the nominal detector resolution, 2 samples per 2σ detector subtense. Again, if this results in an unjustifiably large memory requirement, a compromise can be reached in which the typical radar DSC memory size can be allocated among the number of lines displayed, which determines the vertical FOV, the number of elements per line, which determines the horizontal FOV, and the number of bits per pixel, which determines the video dynamic range.

A somewhat special requirement for the EOLS sensor may be to provide a display of uniform range intervals on the ground between samples, rather than uniform slant range between samples. This requires a special variable sampling frequency, as discussed in section 3.2.

3.8.4 IRST

The IRST systems, as typified by the MA-1 system is an A-A IR search and track system that parallels the operation of the associated radar system in that they generate multibar video traces. This video display data is essentially analog signal data that cannot be displayed on a TV display without scan conversion. A DSC memory as well as mode peculiar timing and control, D/A conversion, and write address generation is required to properly mechanize a DSC for TV display of line trace data.

Since signal intensity in this case is represented by deviation of the trace from some reference position, only one bit of intensity information is required per pixel. The number of horizontal samples is determined from the nominal detector azimuth resolution, 2 samples per detector subtense. The number of vertical samples depends on the number of detectors in the IRST array and the desired signal amplitude quantization. The normal 4 bar MA1 scan quantized to 64 vertical levels, requires only 256 raster lines of a display. Hence this is easily accomplished in a 525 line television raster.

3.9 Display Indicator Design Criteria

The last component in the video chain of a display system is the display monitor itself, i.e., the device which is viewed by the operator. The display monitor has almost always in the past been a cathode ray tube (CRT) or variation thereof, although new flat panel media such as liquid crystal matrix arrays, light emitting diode arrays, and plasma cell arrays are under rapid development and are becoming more and more practical for sensor display applications. The emphasis here, however, will be on CRT displays. We shall also restrict our attention to the display of video data in a television raster format, since sensor data typically is scan converted to TV format. It should also be mentioned that advanced flat panel displays will require input video in a TV format. A full random access capability for such displays would necessitate the use of very complexing addressing.

The bandwidths required of the video amplifiers for different line standards were tabulated in Table 35, in the previous section. For an application requiring a multiple line raster the video bandwidth should be sufficiently high to accommodate the highest line number.

An important question faced by the designer of sampled data display systems is that of what spacing to employ between written elements, i.e., raster lines on the display, in relation to the size of the instantaneous display spot. Various criteria exist in the literature, each of which purports to specify the "optimum" raster line spacing for a given display spot size. Some of these criteria will be discussed here as background information for the basic problem.

The fundamental concept is that a prominent raster line structure on the display has a distracting effect which tends to interface with target detection and recognition performance in an adverse manner. Such a pronounced raster structure has variously been described as a source of noise added to the true video or as the visual analog of the familiar auditory masking phenomenon. The effect of a sharply defined raster structure on video information may be found in "Perception of Displayed Information", (Ref. 9, Biberman).

Among the more popular of the flat field criteria is that stemming from the shrinking raster resolution measurement technique. For a Gaussian display spot intensity profile, it may be verified both analytically and experimentally that the display modulation response to an impulse train input goes to zero when the spatial period of the input is equal to 2σ, where σ is the spot radius, or the standard deviation of the Gaussian expression to next page resulting in 88 percent useful modulation and 12 percent spurious response.

Still another approach might be to determine the raster line spacing such that the spurious raster response or raster induced noise, is equivalent in strength to the lowest displayed gray shade. This occurs at a raster line spacing of 3.5σ which characterizes the spot shape. Since the output modulation for this raster line spacing is in fact equal to zero, or very nearly so, this represents a natural criterion for absence of a perceptable raster line structure.

Others contend that this is too conservative a criterion, and that a somewhat higher level of raster line modulation can be tolerated in a trade for better signal modulation figures. Representation of this is in the paper, "Optimum Spot Size of a Scanner CRT Display", (Ref. 10). In this paper a raster line spacing criterion of 2.6σ is derived and justified as being a better compromize between useful modulations and spurious raster modulation.

Our recommendation is that the shrinking raster flat field criterion is most valid, at least for typical sensor display applications. The reasons for this is that a certain amount of spurious modulation, or raster noise, may be tolerable in a high video signal to noise ratio environment, where the video signal essentially only has to compete with the raster noise. But in the typical sensor display situation, the video signal to noise ratio is not high, and thus to maximize the video signal to noise ratio which the operator sees, one should minimize the amount of raster noise on the display. As previously mentioned, when the raster line spacing is equal to 2σ, where σ is the display spot radius, there is no raster noise.

Earlier in Section 2 visual acuity and laboratory performance studies verified that a nominal sample spacing (or raster line pitch) of 100 elements per inch is a reasonable value. Therefore to be consistent with the desired minimum raster noise criteria, the CRT 2σ spot size should be 0.010 inch. From these criteria the optimum display sizes can be derived based on the total resolution required or, conversely the total resolution (or number of samples) displayed can be derived given the display size. In order to retrofit the MMSDS display into existing aircraft it is very likely that the sensor display will have to stay approximately the same size in order to fit in the cockpit O & M. Therefore, it is not reasonable to provide more resolution (raster lines, picture elements, or memory size) than can effectively be presented on the indicator.

The existing aircraft systems fall into two resolution categories. The F-4, F-106, and A-7 possess 4" displays. Therefore a 525 line raster (100 elements per inch) with 512 picture elements stored is the optimum format. The F-111 display is somewhat larger, approximately 6 inches. This system presently uses a non-standard 787 line raster. The MMSDS system could be used to generate video in this format or one of the standard rasters listed earlier. The B1 will also probably possess an 8 inch display. However, with the higher resolution sensors in the future it is desirable to design the MMSDS system to drive up to a 10 inch display with a 1023 line raster and maximum memory size of 1024 x 1024 elements.

4.0 MECHANIZATION TRADE STUDIES

4.1 Introduction and Summary

Mechanization trade-offs were made in five major design areas to arrive at the optimum design configuration for the MMSDS. These areas were: 1) selection of display sweep formats, 2) determination of basic scan converter architecture, 3) selection of memory type, size, and structure, 4) determination of digital scan converter controller architecture, 5) determination of optimum symbol generator configuration. A summary of the major conclusions arrived at as a result of the trade-off studies is given in Table 36.

TABLE 36. TABLE STUDIES AND CONCLUSIONS

Display Sweep Format

- Television raster format recommended
- Low deflection power
- Simple composite video interface
- Ease of retrofit into existing display systems
- Simple television video recorder for recording
- Compatible with advanced flat panel displays

Digital Scan Converter Architecture

- Programmable controller recommended
- Modular memory
- Separate input video processor/buffer function
- MUX data control bus
- Separate high speed input address generator

Memory Selection

- MOS random access memory recommended
- Low power (< 100 μw/Bit)

(Continued next page)

(Table 36, concluded)

- Inexpensive (~1¢/bit)
- 256 x 256 x 1 bit recommended module size
- Flexible single bit addressing
- High data rate parallel addressing mode
- Memory module to include flexible buffer for interface
- Growth to charge-coupled-device

Controller Design

- Programmable microprocessor a chitecture recommended
- System changes by ROM programming
- Common design for DSC and Symbol generator
- Provides mode control, address control and built in test functions
- TTL mechanization
- Fast (<1.0 μsec cycle time)
- 16 bit word size

Symbol Generator Design

- Programmable in-raster symbol generator recommended
- Buffer memory for conversion to raster format
- Uses same memory module as digital scan converter
- Uses same controller design as digital scan converter
- Software changeable symbol shape and repertoire
- All digital components

4.2 Display Sweep Format Selection

One of the key mechanization decisions that must be made in the design of a display system is the selection of the format and structure of the display sweeps. The sweep formats influence the deflection amplifier requirements, the symbol generator design, the sensor scan-conversion requirements, and the type of data recording. The selection of an optimum format for a specific display system application involves the evaluation of a number of diverse factors. The final format selection is usually a compromise to provide the best performance for the minimum cost. In determining the sweep formats for the Modular Multi-Sensor Display System emphasis was placed on establishing a standard scan format that would be compatible with multiple system applications, minimize the display indicator complexity, assure phosphor protection against burns during sweep failure, and be compatible with video tape recording and playback, either airborne or ground based. Compatibility with advanced flat panel matrix displays was also considered.

Three basic display sweep mechanization alternatives were studied:

1. Raster — Sensor data and symbology is presented in a standard horizontal television raster.

2. Stroke — Sensor data is presented with linear sweep generation formatted for the specific mode (B-scan, PPI, etc.) and all symbols are stroke written.

3. Hybrid — Sensor data is presented in a standard horizontal television raster and symbols are stroke written during frame retrace time.

These three mechanizations were evaluated with respect to the following major criteria: image quality, mechanization complexity, system modularity and growth features. A summary of the trade off analysis is shown in Table 37.

4.2.1 Radar Image Quality

In the orthogonal scan formats (B, sidelooking, TF) there is no difference in image quality or display appearance for either a TV raster or stroke display format since both provide an orthogonal transformation or mapping of the radar data to the display surface. However, in the PPI modes, there is a major difference in the transformation of the data from the radar to the display surface as a function of whether a TV raster or PPI format (arc-scan or radial sweep) is generated on the display. Whether this results in a significant difference in image quality or display appearance depends on the radar resolution characteristics and the DSC spatial quantization. The TV raster display presentation is characterized by constant X and Y resolution elements, ΔX and ΔY, where ΔX is the display width divided by the number of horizontal samples and ΔY is the display height divided by the number of television scan lines.

TABLE 37. STROKE VERSUS RASTER DISPLAY COMPARISON

Parameter	Raster	Stroke	Hybrid
IMAGE QUALITY			
SENSOR DATA			
Orthcgonal Formats (B-Scan, TV, FLIR)	NO DIFFERENCE BETWEEN APPROACHES		
PPI Format	Constant X and Y resolution element size, uniform display element spacing, range and azimuth resolution varies as a function of position on display.	Constant range and azimuth resolution element size, non-uniform display element spacing may result in spoking, better azimuth resolution near the apex, better range resolution at off boresight angles.	Same as Raster
SYMBOLOGY			
Grids, Scales Alphanumerics	NO DIFFERENCE BETWEEN APPROACHES		
Circles and Vectors (Horizon line)	Spatial modulation of lines due to discrete quantization Approximately 50 to 100 percent wider symbol line widths	Smooth continous lines	Same as Stroke

(Continued next page)

(Table 37, concluded)

Parameter	Raster	Stroke	Hybrid
MECHANIZATION COMPLEXITY			
CIRCUIT COMPLEXITY (RELATIVE)			
Symbol Generator	1.5	1	1
Deflection Amplifier	1	2	3
Scan Converter	1	1	1
DEFLECTION POWER			
Peak	40 W	160 W	160 W
Average	40 W	160 W	80 W
Heat Dissipation	No Problem	Possible Problem	Possible Problem
WEIGHT (Normalized)	1.0	1.10	1.00
MODULARITY			
Interface	Single line composite video	X, Y, Z interface	X, Y, Z interface
Retrofit	Can use existing TV mode in indicator	May require modification to the indicator	May require modification to the indicator
GROWTH FEATURES			
Recording	Simple TV video recorder	Requires complex recorder	Requires complex recorder
Flat Panel Display Compatibility	Simple	Complex	Complex
CONCLUSION	Recommended	–	–

The linear sweep PPI format (arc scan or radial sweep) provides constant range and angular resolution elements, ΔR and $\Delta\theta$, where ΔR is the range scale divided by the number of range samples and $\Delta\theta$ is the azimuth scan width divided by the number of azimuth samples. Radar resolution is defined in terms of the pulse width in range and the antenna beamwidth in angle and therefore corresponds to the linear sweep format resolution parameters. The TV raster resolution parameters must, therefore, be converted to equivalent radar resolution elements in order to compare the performance of the two systems. A complete analysis of the TV compatible resolution is provided in Section 3.8.

The results of this resolution analysis indicate the requirement for approximately twice as many resolution elements in the TV compatible PPI display as in the radial or arc scan PPI display to provide the same resolution quality. However, the radial scan display exhibits severe "spoking" when limited to the minimum number of azimuth samples required, and therefore, normally requires considerable more samples to maintain an acceptable display quality. Thus, the radial scan display normally will require as many resolution elements as the TV compatible display.

4.2.2 Symbol Image Quality

The symbols to be displayed can be broken into two major types: straight line segments either parallel or orthogonal to the raster, and conics and straight line segments at an angle to the raster such as the horizon line. The first type of symbols are equally displayed by in-raster or stroke techniques. Large conics and vectors however are of slightly higher quality when stroke generated. The in-raster generated vectors contain some spatial modulation due to the line sampling. This results in slightly wider symbol line widths, since the symbols are normally written on both raster fields. Techniques of minimizing the spatial modulation such as field to field interpolation and overlapping of adjacent lines provides good quality symbology.

4.2.3 Mechanization Complexity

Block diagrams of the alternate mechanization are shown in Figure 77. Key differences are apparent in the PPI address generator, sweep generation, symbol generation and display deflection circuitry. The raster mechanization requires more complex input address generation and symbol generation and less complex output circuitry. The stroke mechanization requires simpler input address and symbol generation and more complex sweep generation and output circuitry. The hybrid mechanization require both the more complex input addressing and output circuits. One advantage in favor of the raster approach is the minimal use of analog circuitry which results in fewer adjustments than are required in the stroke and hybrid system. Due to the variation in writing speed on the linear (arc scan) display, an analog function generator is required to insure equal brightness over the entire display in the stroke alternate.

The display required for the stroke and hybrid approach is more complex than the TV monitor type display. High power linear deflection is required in lieu of the tuned deflection circuitry. The basic advantage of

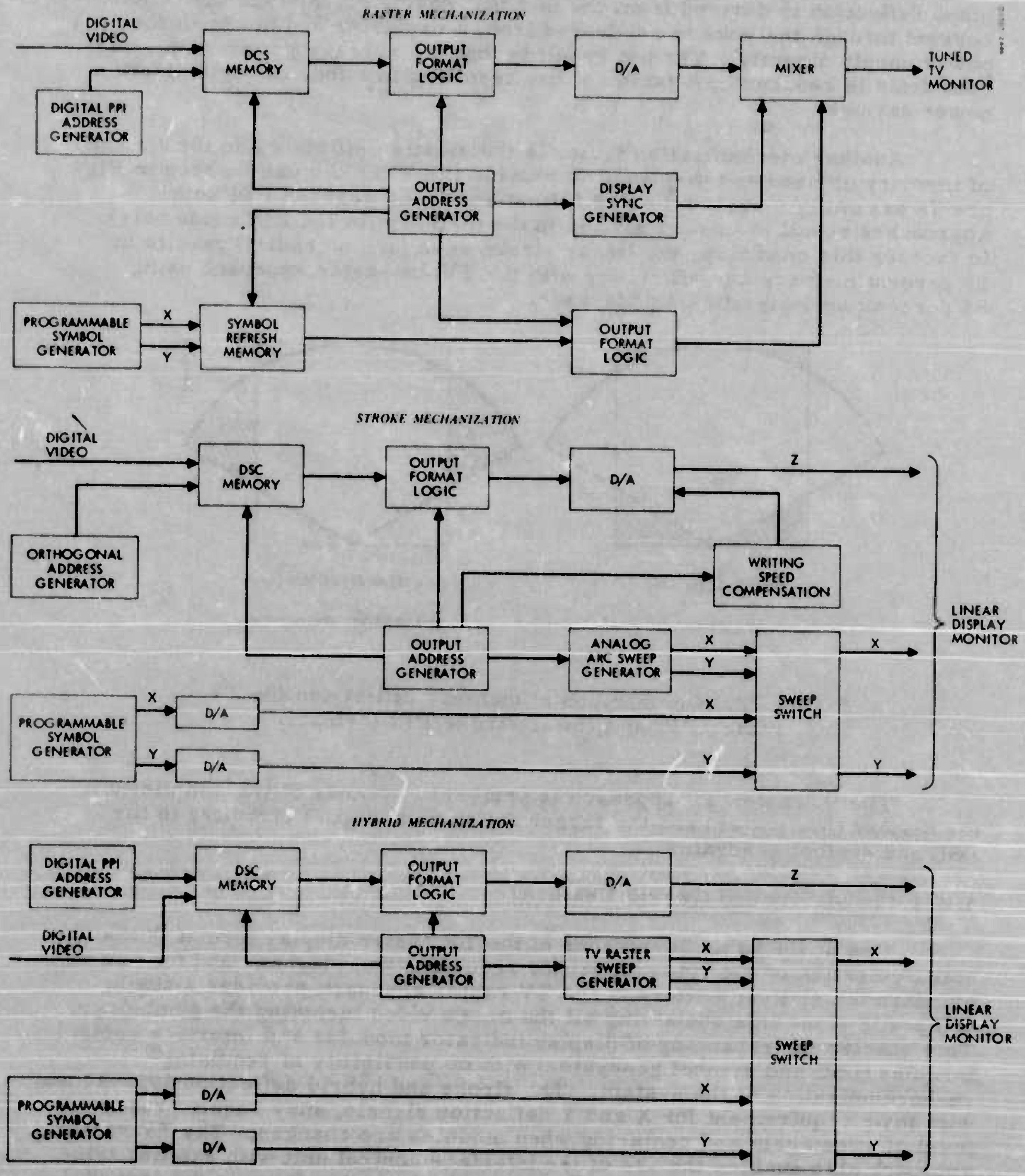


Figure 77. Alternate mechanizations.

tuned deflection is derived from the fact that during retrace the deflection current through the yoke is recovered from a capacitor and not from the power supply directly. The net result is that the average power supply current drain is reduced by a factor of two resulting in a four to one deflection power savings.

Another mechanization factor is the relative efficiency in the amount of memory utilized and displayed to provide the PPI. As can be seen in Figure 78 assuming a square display format and a ±60 degrees PPI both approaches result in unused portion in the memory (in the PPI mode only). In fact for this condition, the linear stroke scan (arc or radial) results in 86 percent memory use efficiency with the TV-in-raster approach using 84 percent; an insignificant difference.

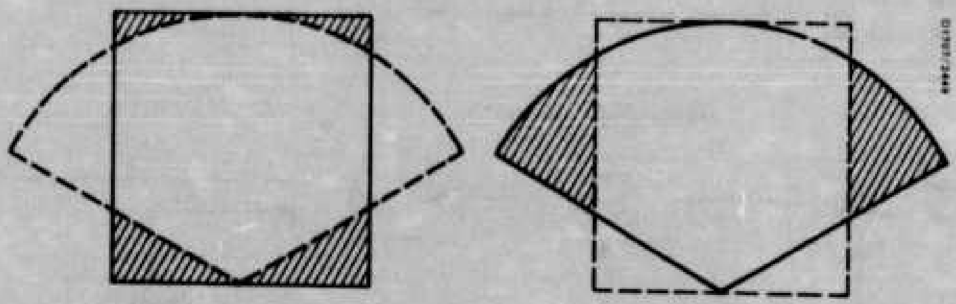


Figure 78. Comparison of memory utilization for TV raster PPI and linear stroke PPI formats.

The in-raster TV approach is preferred because of the simplicity in the display (low power) and the larger reliance on digital circuitry in the DSC and symbol generator.

4.2.4 Modularity and Growth Features

One of the basic advantages of the TV raster display format is the standardization of the video signal for recording and playback and for use on standard television monitors. The TV raster approach provides a single composite video line containing all the image video including the symbology. This enables interchanging of display indicator modules and interface control modules (DSC and symbol generator) with no possibility of requiring re-harmonization of the system. The stroke and hybrid deflection approaches, with their requirement for X and Y deflection signals, may require readjustment of sweep gain and centering when modules are changes. The TV raster approach also enables the use of the interface control unit with existing television compatible display indicators either in the aircraft or on the ground.

The capability of recording both the radar data and the superimposed symbology, especially in the track modes, on a standard video tape recorder for playback on a standard television monitor is a major advantage of the TV compatible approach. This reduces the ground support equipment required for recording playback to a tape playback unit and a standard 525 line monitor. No special interface or signal processing equipment to reconstitute the display is required. This enables making maximum use of the recording capability. Also, another area of growth potential is that of interfacing with a flat panel display. The results of a recent AFAL contract conducted by Hughes indicated that the optimum input format for a flat panel liquid crystal display was a standard television type format. Random access display addressing required by the stroke (and hybrid) scan approach would significantly complicate this interface.

4.2.5 Conclusions and Summary

A summary tradeoff table of the major factors was shown in Table 40. From this analysis, the conclusion is that the in-raster television approach is preferred. This approach offers a simplified mechanization with better growth potential in a form that is easily modularized. A photograph of a TV compatible PPI digital scan converted display is shown in Figure 79.

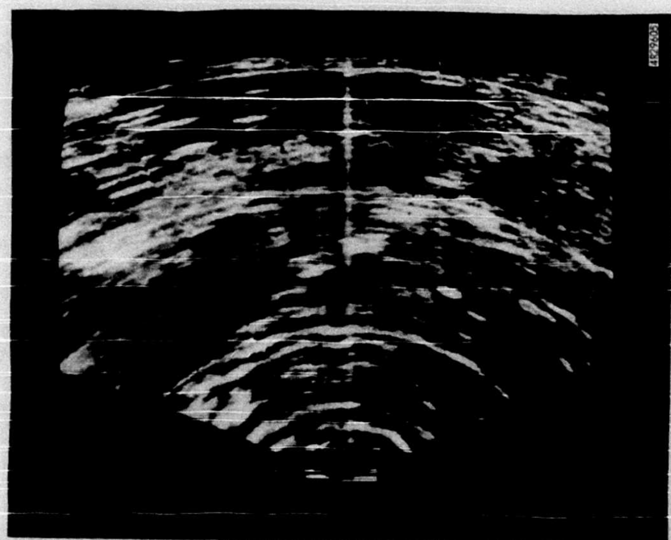


Figure 79. TV compatible PPI display using simulated low PRF radar video.

4.3 Digital Scan Converter Design Evolution

Figure 80 illustrates an idealized Modular Multi-Sensor Display System. Radar, FLIR, or TV video is converted to digital numbers. An ultra-high-speed processor accepts the data and performs a number of subroutines to integrate, peak detect, truncate, and store the processed data. Meanwhile, other routines are reading out the correct addresses to produce the TV video output and generate sync signals. Although highly desirable, this display system requires a processor capable of nanosecond additions or faster and a memory capable of very fast (~60 MHz) input/output word rates. This concept for the MMSDS is not considered feasible at this time.

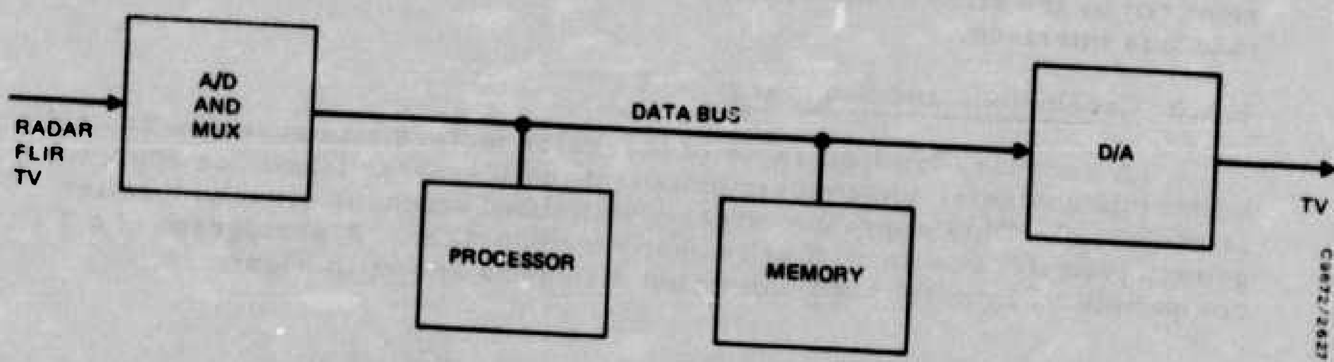


Figure 80. Ideal modular multi-sensor display system.

Since the raw input data is arriving at the same time display data must be read out, simultaneous occupation of the data bus would occur in the idealized system. A solution to this problem is to use a two-port memory so that new data can be entered from one side concurrent with display data readout. This essentially breaks the data bus into two parts, an input data bus and an output data bus.

Now if we look at the rates of data entering and leaving the display system, the required speed of input and output addressing for the main memory can be calculated. The output rate is simpler as it is always TV format. The maximum output rate occurs for the highest resolution display. The maximum rate is therefore:

$$\frac{(1024 \text{ display elements})^2}{\text{frame}} \frac{(30 \text{ frame})}{\text{sec}} \frac{(4 \text{ bits})}{\text{element}} \approx 120 \text{ MHz display bit rate.}$$

If one word equals one display element, the word rate is 30 MHz. That is, the output addresses must be calculated at a 30 MHz rate. This rate exceeds the capability of state of the art processors and memories. Therefore, a dedicated output address generator must be added to the design and input/output formatting logic must be added to the memory to spread out and slow down the input/output rate. The new design architecture is illustrated in Figure 81.

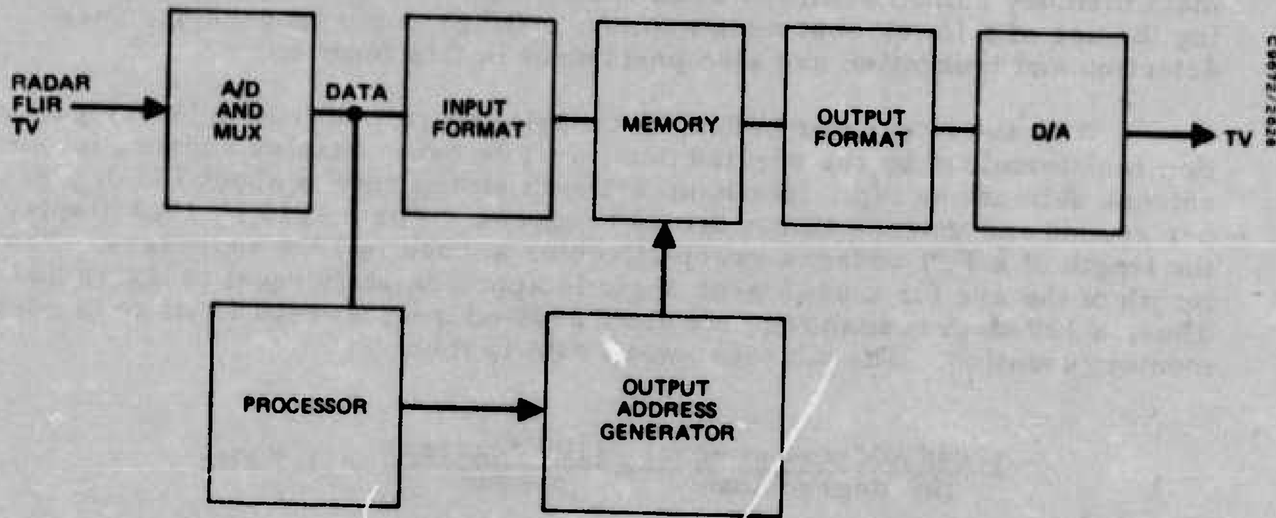


Figure 81. Modified modular multi-sensor display system.

The input data rate varies considerably due to the different sensors accommodated. With a particular sensor and a display format we can compute one of the required input address generation rates. Consider a radar input to be presented in a PPI mode on a 1024 by 1024 display. The scan conversion required is given by the formulae:

$$x = n_1 \sin\theta$$

$$y = -\frac{Ny}{2} + n_1 \cos\theta$$

where

θ is antenna azimuth angle

$x = 0, y = 0$ is center of display

n_1 = the range element count and varies from zero to 1024

N_y = 1024, the number of display elements in the y direction.

A total of 1024 elements will be sampled from the radar video for each radar range sweep. Range sweeps occur at rates from 250 to 2000 Hertz. So the input element rate may be as high as (1024) · (2000) = 2.048 MHz. So that a new input element arrives about every 500 nanoseconds. Two 10 - bit addresses (X and Y) are needed at that frequency to store the input elements. Since individual processor steps occur at roughly this same speed, very minimal, if any data manipulation would be possible. Since the radar data is normally integrated to improve the signal to noise ratio of the video, the next logical step is to include an integration module to provide both the processing and input buffer function. Thus, the input loading to the main memory can be achieved when desired and slowed down, thereby allowing the use of a lower cost main memory. Other video processing, peak detection and truncation are also performed in this function.

With the integrator buffer, the maximum rate of input address generation is determined by the requirement to write every display address in one antenna azimuth sweep. Maximum azimuth sweep rate is about 100 degrees per second and antenna limits are ±60 degrees. For a 1024 by 1024 display the length of a PPI address sweep at center screen is 1024 addresses. The length of the arc for a 60-degree angle is approximately equal to the radius. Thus, a 120-degree scan requires about 2048 address sweeps to write in each memory location. The address sweep rate is then:

$$\frac{(2048 \text{ address sweeps})}{120\text{-degree Scan}} \times \frac{(100 \text{ degrees})}{\text{second}} = 1.7 \text{ kHz}$$

Since each address sweep covers 1024 addresses, the maximum element address rate is:

$$(1024) \times (1.7 \text{ kHz}) = 1.75 \text{ MHz}$$

At this rate a 1024 by 1024 display has each address at the limit of the radius generated once per azimuth scan. Addresses nearer the sweep start point will be generated many times. An actual display is probably not this demanding due to cut offs at screen edge. However, this maximum rate must be obtained for the mid-screen address sweeps. Since several arithmetic functions are involved in generating each memory address, this rate is beyond the capabilities of a processor so a special input address generator must be added. This address generator is directed by the controller which generates address starting points and slopes from which the input address generator generates the specific memory addresses.

The resulting recommended digital scan converter architecture is shown in Figure 82. Input video is A/D converted, processed (and buffered) and stored in the main memory for continuous display refresh in a TV format. Input and output memory addressing is achieved in address generators controlled by a microprocessor type controller. In addition to address control, the controller sets the processing parameters and selects the desired input video as a function of the selected mode. It also performs the unit Built-in-Test function.

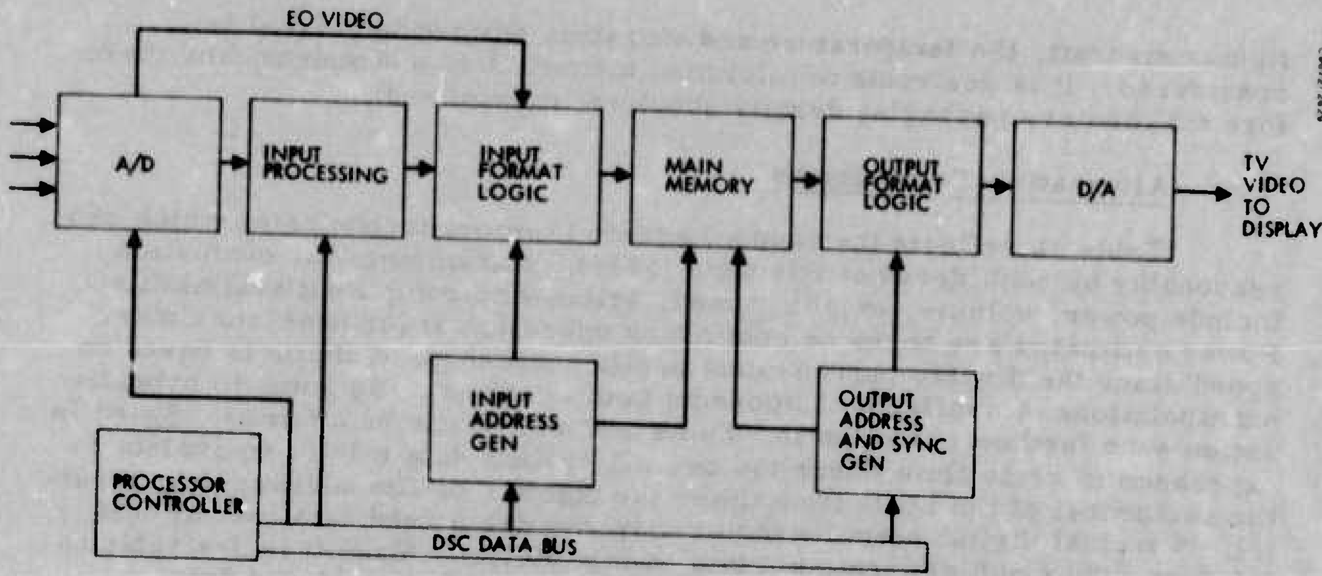


Figure 82. Final MMSDS digital scan converter architecture.

4.4 Memory Trade-Off Study

After selection of the display format and overall scan converter architecture the next most important task is the definition of the optimum memory type and structure. For the modular application, this memory must be modularly expandable and capable of providing a TV output format with a multiple sensor loading format. More specifically, it must be capable of being loaded in all the system radar formats (and line scan EO formats) to provide the scan conversion function and it must be able to provide a TV frame (or field) freeze capability. The flexibility required to provide these functions dictates the use of a random access memory at the present time. It is likely that advanced serial access memories (Charge Coupled Devices) will become competitive in price in the future and compete for use in this application. Therefore, at the conclusion of this section, the application of serial access charge coupled devices is discussed.

4.4.1 Memory Type Selection

Evaluation Criteria

The concept of a modular digital scan converter indicates the use of core memory modules which comprise the building blocks of the memory system. This module should be random addressable to provide the addressing flexibility compatible with the decision to provide all displayed information in a TV raster. It must be low power, since for some applications millions of bits must be stored. Non-volatility is not required since the entire memory is updated in a matter of seconds in all modes. Since the digital signal transfer unit may be in the equipment bay of a high performance fighter aircraft, the temperature and vibration environment must be considered. It is desirable to minimize the unit size and weight, and therefore the memory packaging density should be maximized.

Alternative Technologies

Table 38 reflects the random access memory technologies which can reasonably be considered at this time (1974). Parameters for evaluation include power, volume, weight, speed, price, and component availability. Power estimates are based on continuous operation at (or near) maximum speed since the display must be continually refreshed. Volume is based on extrapolations of available components (and systems). By going to hybridization even further reduction in volume and weight can be attained. Speed is expressed in cycle time where the overall system data rate is equivalent to the reciprocal of the cycle time times the number of bits addressed in parallel. A typical digital scan converter may require a read data rate of 30M bits/sec (500 x 500 elements x 4 bits each x 30 Hz). Since it is desirable to time share at least on a 50 percent basis with the writing of new data, a 60M bit/sec minimum data rate is required. Therefore a cycle time of 1 μsec would require addressing 60 bits in parallel. The prices are based on estimates to provide production memory systems suitable for use in airborne military aircraft.

Memory Selection

The baseline selection for this application, at this time, is dynamic MOS RAM. The actual selection of P or N channel should be made during the detail design to reflect the latest tradeoff factors. Both provide relatively low power operation, small size and a low price. The cost of ownership is reduced over core and plated wire since they are easily repaired. Core and plated wire failures are extremely difficult to repair.

4.4.2 Memory Format

The actual size and configuration of the recommended memory module was determined by alternately considering the input and output format requirements, module size and memory size requirements of the various applications. The minimum memory size increment is 65,536 bits. It represents a display configuration of 128 x 512 elements (F-106) or 256 x 256 elements with a one bit video level. It is obtained with 16-4096 bit MOS RAM devices. One bit level was selected to provide maximum flexibility since 2 bit levels would force systems into an even number of quantization levels. For maximum flexibility the 4K x 16 memory arrangement must be single bit alterable that is, one bit can be changed in one memory cycle without modifying the other 15 bits of the data word. One bit addressing is required since the integrator is unloaded one element at a time and the PPI (and side looking modes) cannot be loaded with several elements in parallel at the same address. This requirement is shown in Figure 83. The multiple bit video and symbol generation requirement is obtained by building up the display using these memory modules as shown in Figure 84.

TABLE 38. TYPICAL CHARACTERISTICS 1973/74 RAM TECHNOLOGY

	*Reliability 1M Bit Memory, hours	Power, Watts/ M Bit	Volume/ M Bit, in.^{3}	Weight lb./ M Bit	Cycle Time, μsec	Price/ M Bits, $K	Comments
Core	2,000	300	700	25	0.60	25	Nuclear hardened Difficult repair
Plated Wire	2,000	100	500	20	0.30	40	Nuclear hardened Difficult repair
MOS RAM							
P Channel dynamic	1,000	65	200	8	0.60	10	4K bit chips in production
N Channel dynamic	700	80	500	20	0.40	20	Small quantity, production now
N Channel static	800	40	450	18	1.0	30	Simple interface
MNOS RAM	800	400	450	18	1.0	40	Radiation hardened
Bipolar Ram	800	500	450	18	0.05	100	Radiation hardened

*Assumes B Level Components

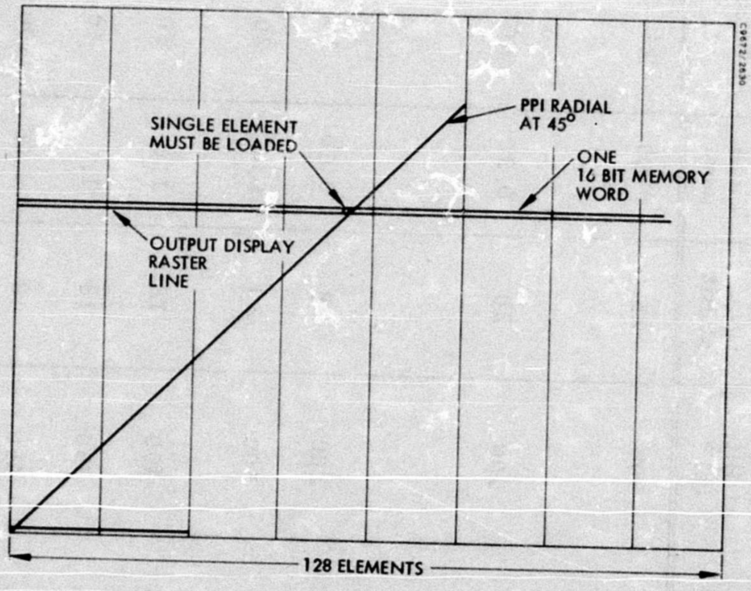


Figure 83. Mapping of 16 bit memory word on display raster illustrating requirement for single element addressing in PPI mode.

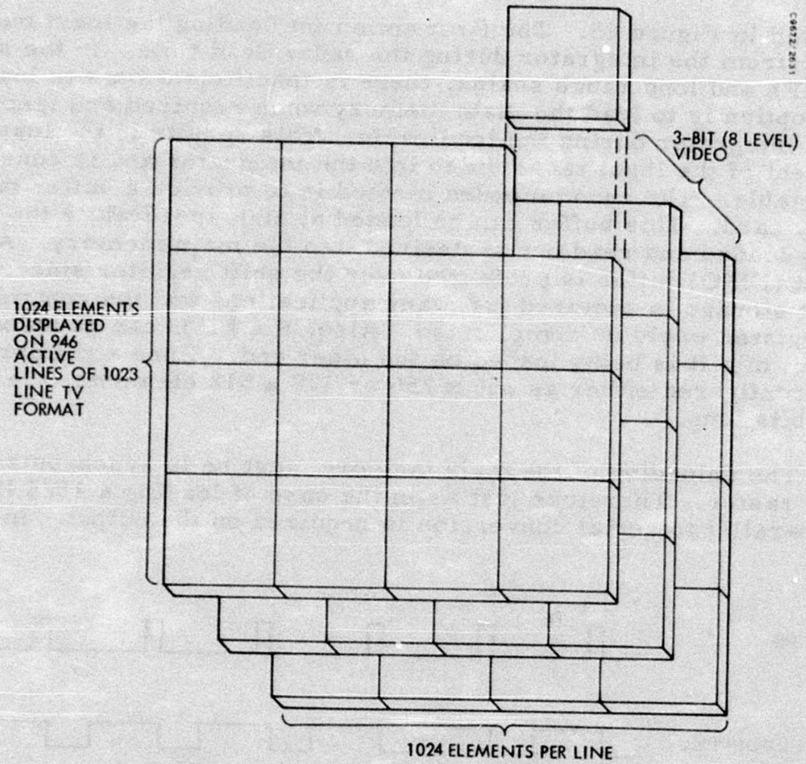


Figure 84. 1024 x 1024 x 3 bit display configured from 256 x 256 x 1-bit memory modules.

In addition to the single bit loading capability, parallel multiple element loading must also be provided for a television freeze capability. Memory module configurations up to a 1023 line x 1024 element capability for system growth is necessary. The active line time of 1023 line video is 25.6 μsec. Therefore to load 1024 elements a single bit at a time would require a memory cycle time of 25 nsec. This is beyond the capability of the recommended MOS memory technology. To provide the 1024 x 1024 capability, 16 memory modules are required for each bit level stored (shown in Figure 84). Since each module can accept a 16 bit word, a cycle time of 400 nsecond is adequate. This is obtainable with N channel MOS RAMS. Therefore two input formats are required, a single bit load mode and a 16 bit serial to parallel converter for maximum loading rate of the 1023 line TV frame freeze.

Analysis of the radar data loading revealed that data cannot be transferred directly from the integrator into the main memory without excessive loss of input data into the integrator. This happens because the main memory and the input integrator cannot simultaneously be loaded. This problem is illustrated in Figure 85. The first option for loading the main memory is to transfer from the integrator during the radar dead time. In the systems with high PRFs and long range scales, there is insufficient time to load data. The second option is to load the main memory when required and ignore input data into the integrator during the load cycle. This results in the loss of up to 25 percent of the input radar video into the integrator and is considered unacceptable. The recommended method is to provide a buffer on each memory card. This buffer can be loaded at high speed while the integrator is being loaded and read out as desired into the main memory. A first in — first out (FIFO) buffer is preferred over the shift register since variable element storage is required for many applications and the control logic for a shift register would be complicated. Also, the FIFO can be unloaded from one end while it is being loaded on the other end. Since a memory module can be configured either as 256 x 256 or 128 x 512 elements, the FIFO must be 512 bits long.

The unloading of the main memory must be in synchronism with the display raster. Therefore just as in the case of loading a 1023 line format, 16 bit parallel to serial conversion is required on the output. In addition to

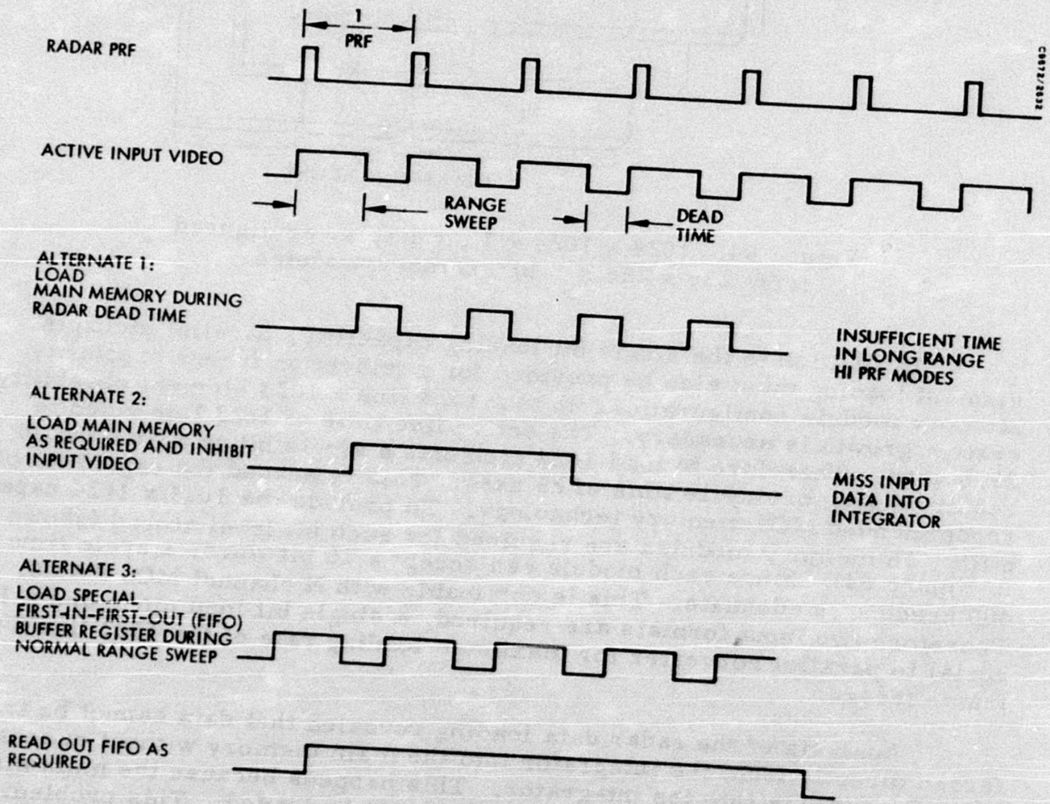


Figure 85. Alternate timing considerations for transferring data from input integrator to main memory.

the high speed unloading required for display refresh, a lower speed readout is provided to transfer data to a data-link or computer. In this mode the output display is blanked for a short time until a complete frame is transferred. Also a display freeze mode of any sensor video is provided by inhibiting memory loading and continually reading the stored data. The resultant memory function possesses two input loading modes, a FIFO buffer, the memory and output format logic. The detail module design is presented in Section 5.0 of this report.

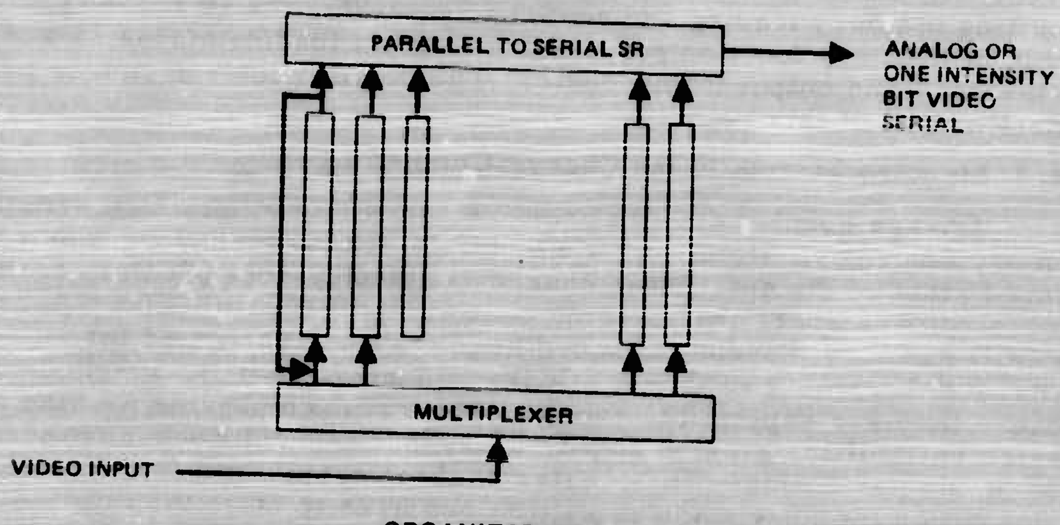
4.4.3 Memory Module Using Charge Coupled Devices

Charge coupled devices promise to provide a very high density, low cost memory functions. However, it will be several years before they can be considered state of the art. When charge coupled devices (CCDs) reach the stage of development where they become cost competitive with MOS RAM memories, the CCD memory module described here may be substituted for one or more digital RAM memory modules. CCD memories are being watched with interest because they are expected to eventually offer much greater packing density, greater reliability, greater speed, lower power, and lower cost per bit than MOS or bipolar RAMs. The greater packing density and lower power of CCDs means fewer memory modules will be required to store the digitized image in high resolution systems. Since CCDs can be low noise analog devices, the image may be stored in its analog form. This will allow reduction in memory size by a factor equal to the equivalent number of intensity bits. However, analog CCD technology is currently severely limited in terms of storage time available and will probably not be applicable for several years.

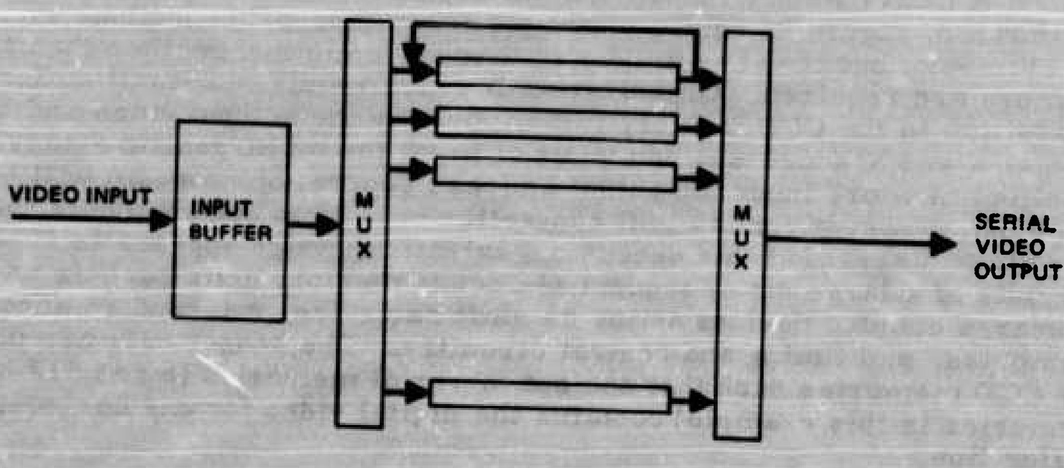
Mechanization

A CCD memory module can be organized in two ways. Organization A as shown in Figure 86 can be used only for orthogonal coordinate conversion or TV freeze but is very efficient in that few components other than the CCD memory are required. Organization B which requires a small buffer memory in addition to the CCD memory to temporarily store input video and incremental X and Y addresses can be used in all the multi-sensor modes. A modified memory input and output address generation program will be required, however for the DSC controller module to accommodate the CCDs. The block diagram of this second organization, which appears in Figure 87, consists of a large set of sequential access memory units such as an array of charge coupled devices acting as shift registers, two random access buffer memories, and timing and control circuitry. The sensor data are placed in the CCD memories such that one set of serial memories (three 512 bit memories in this example) contains the digital video for one horizontal display raster line.

While all memories shift in synchronism, the PPI data is entered in a staggered fashion so that only one bit of data need be entered into the memory matrix during any clock interval. Therefore, a radial line of PPI data can be entered into the memories in a small fraction of the display frame time. The data continue to shift for eight clock intervals, during horizontal retrace, after the active memory has transferred its data to the display. This added shifting brings the first data in the next memory up to the front, compensating for the input address staggering. The data out of the memory matrix, during the active display line times, appears in the proper order as



ORGANIZATION A



ORGANIZATION B

Figure 86. Alternate serial memory organizations.

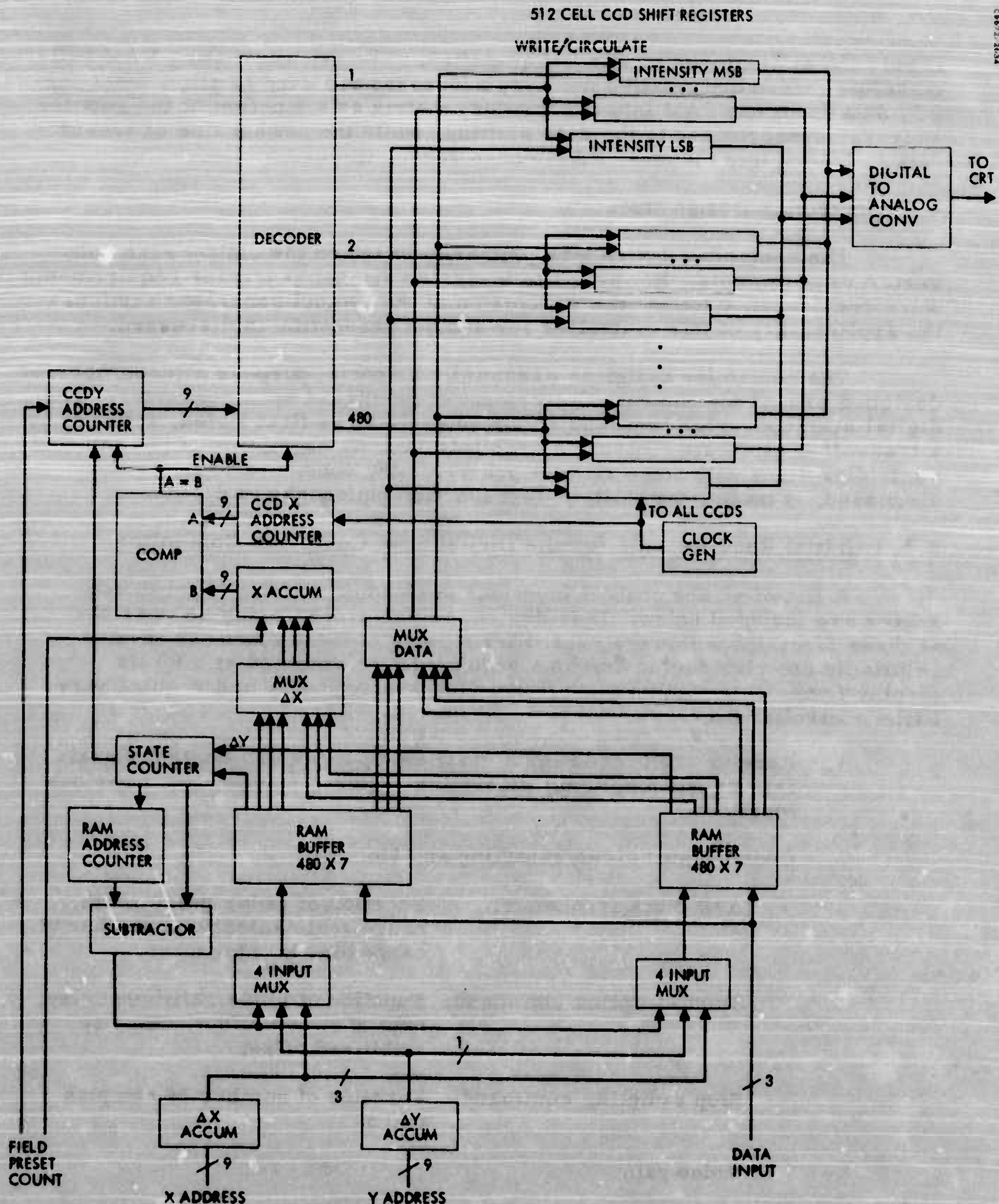


Figure 87. Display coordinate converter for a sequential access memory detailed block diagram.

if only the active memory was being shifted. The two alternating RAM buffers containing video and relative memory addresses are used to allow inserting PPI data from one RAM into the memory matrix as a function of the relative address, synchronized to the data shifting, while the newest line of sensor data is loaded into the other RAM under sensor timing.

4.5 Controller Design Study

The controller design was primarily based on the digital scan converter requirements. However the in-raster symbol generator requirements were considered also. At the conclusion of the symbol generator section, the applicability of this controller for symbol generation is discussed.

The controller design is essentially a special purpose microprocessor designed around the control requirement of the digital scan converter. The digital scan converter functions of the controller are first listed, followed by a tradeoff of alternate controller architecture. A description of the selected controller along with some sample programming considerations are then discussed. Finally, the built-in-test function philosophy is discussed.

4.5.1 Initial Requirements for the Digital Scan Converter Controller

A list of all the control functions performed in a digital scan converter are included below. It is desired to perform as many as possible of these functions within the controller. Some of these functions involve relatively complex data operations which must be executed at a 60 Hz display frame rate. Others occur relatively infrequently and require very little controller time.

1. Receive and decode input data; set up mode and control signals for various functions; determine required constants for various functions.

2. Control input video sampling and storing:

A/D clock frequency:	Function of radar pulse width, range scale selection, number of range bins in integrator.
Start sampling command:	Function of mode, altitude delay, expand sweep offset, velocity stabilized offset
Stop sampling command:	Function of number of samples taken
Video gain	
Video offset bias	

3. Control video integration and intensity transfer function

Integration feedback constant:	Multiplying factor — function of beamwidth, PRF, antenna scan rate
Integrate:	Addition — number of bits in adder and accumulating register
Peak detect:	Compare — number of range bins collapsed function of main memory size-integrator memory size
Truncation:	Transfer function shape — gain factor

4. Load and store video in display refresh memory

Frequency of sampling integrator:	Function of mode, horizontal resolution, antenna scan rate
Coordinate conversion: (Write address generation)	Function of mode — B-scan, PPI, PPI expand, E-scan, SLAR, ground range corrected, TV, FLIR, etc.
Out of scan limit erasure	

5. Special processing in memory

   Integration — multi-frame aging

   Motion Compensation — passing scene — (PPI)

   Dynamic range adjustment — histogram equalization

6. Read out display refresh memory in display format

   Read address generation

   Display synchronization

7. Special functions

   Freeze data in memory

   Erase data in memory

Terrain Following and Ground Range Clock Generation

Data link

8. Built-in-test

4.5.2 Controller Architecture Selection

Four possible architectures were considered to implement the Digital Scan Converter Processor/Controller. They are described in the following paragraphs and pertinent characteristics are compared in Table 39.

General Purpose Minicomputer

One of the first possibilities considered was to use a general purpose minicomputer of the type commercially available. Such a machine is designed to perform as a small stand-alone data processor, a process controller, and/or as a peripheral device in a larger computing system. The design objectives for these machines (off the shelf) are to have absolute low cost even at the expense of performance. Interconnections are minimized by using bus architectures and byte (partial word) at a time internal operations, rather than full word operations. Speed is usually sacrificed to reduce cost for a competitive market. To the user the machine appears to be equivalent to larger machines in language and accuracy but much slower than a big computer and with much less memory available. Operations are performed primarily in the standard fetch and execute mode. In this mode two memory words are used for each operation. The first word establishes a machine state (defines arithmetic operation) and the second word contains the data to be operated on. The number of memory locations required compared to the number of program steps is called overhead and for the general purpose minicomputer the overhead is at least 100 percent. This overhead is not objectional when many different types of programs are to be run on the same machine, but for a special purpose machine this flexibility causes inefficient memory use, slower operation, unnecessary weight, and excessive parts. Therefore it appears inappropriate for this application.

General Purpose Microprocessor Computer

The microprocessor computer is based on MOS integrated circuit processing unit fabricated on a single chip or on a few chips. This type processor is used extensively in portable hand calculators. It is relatively slow compared to most minicomputers. Generally it runs even slower than its associated memory. Althouth appealing due to their small size and few chips, these processors are much too slow for this application.

Direct Functional Mechanization

In this type of mechanization, hardware is uniquely designed to achieve the required function. This type of design usually results in the minimum amount of circuitry and the fastest machine, but it is the least

TABLE 39. TABLE OF ALTERNATE ARCHITECTURE CHARACTERISTICS

	General Purpose Minicomputer	General Purpose Microprocessor	Special Purpose Programmable Controller		Direct Functional Mechanization
I.C. Type	TTL	MOS	TTL	ECL	TTL
Data Word Size	8 - 18 bits	4 - 16 bits	16	16	As needed
Speed (Cycle Time)	Medium (1 - 4 μs)	Slow (5 - 30 μs)	Fast (0.5 - 1 μs)	Very Fast (<0.5 μs)	Very Fast (<0.5 μs)
Number of Instructions	64 - 128	45 - 64	32	32	—
Memory Type	ROM + RAM	ROM + RAM	ROM	ROM	—
Instruction Method	Fetch and Execute — Some Microprog.	Fetch and Execute — Some Microprog.	Microprog.	Microprog.	Sequential Hardware
Mechanization Complexity	1.3	0.8	1.0	1.2	1.1
Parts Cost	High	Low	Low	High	Low
Design Cost	Low	Medium	Medium	High	High
Flexibility	Virtually Unlimited (Limited by Speed)	Very High (Limited by Speed)	High	High	Very Limited
Noise Immunity	High	High	High	Low	High
Programming Cost	Low	Medium	High	High	None
Package Size	Large	Small	Small	Small	Small
MIL Spec.	Yes	No	Yes	Yes	Yes
Conclusion	Inefficient Too Slow	Too Slow	Recommended	Too Expensive Growth Possibility	Not Flexible

flexible. The lack of flexibility would be undesirable in a modular system because it couldn't be adapted to control different systems and different modules without extensive hardwired modifications.

Special Purpose Programmable Controller

A special purpose programmable controller is a control unit designed with a particular application in mind and utilizing a control program to sequence operations. It is essentially a processor structured to fit a particular class of applications. Speed of operation and simplicity of design are obtained by considering the special purpose when designing the machine and flexibility is retained by using program control. This is the most appealing architecture for the digital scan converter in terms of speed and flexibility. Two different technologies were considered for mechanizing the special purpose controller: emitter coupled logic (ECL) and transistor transistor logic (TTL).

The possibility of using the emitter coupled logic family to build a very fast processor/controller to reduce physical hardware was studied. Use of the fastest MECL circuitry, with its one nanosecond switching times, driving a fifty ohm load, requires great care in physical layout. With such fast switching times conventional printed circuit boards must be replaced by striplines and ground plane techniques. A dual arithmetic unit (MC 1686) in this family adds two bits to two bits in 3.0 nanoseconds (1.5 ns per bit) and is the most complex package available. For comparison a TTL high speed arithmetic logic unit (SN 54181) with look ahead carry (SN 54182) can add 16 bits to 16 bits in 36 nanoseconds (2.2 ns per bit). So the gain in speed through the use of ECL is about 1.5 ns versus 2.2 ns in this case. Without the look ahead carry the SN 54181 requires add times of about 4 ns per bit. MECL III then looks about 2-1/2 times faster. MECL II is slower than MECL III and has an add time of about 4.5 ns per bit. MECL 10,000 lies somewhere in between in speed but has several attractive features. The 4 bit Arithmetic Unit MC 10181 adds 4 bits to 4 bits in about 7 ns (1.75 ns per bit). This family has relatively slow rise and fall time to allow the usual printed circuit layout techniques and point-to-point wiring. It also has transmission line drive capability.

In summation, the use of emitter coupled logic would appear to give a speed increase on the order of 2 to 2-1/2 for additions. Other logic operation speeds might be increased even more. This means the ECL controller might do about 3 - 4 times as much data manipulation as the TTL controller. This would certainly allow the DSC controller and symbol generator controller to be combined with the additional possibility of performing the input address generation. The speed increase is costly, however. The ECL circuits are about 2 - 3 times the cost of TTL circuits and many more would be required. Reliability might be reduced as ECL has a much lower noise margin than TTL and some TTL would still be needed. TTL switches from low current to high current states and this causes noise on power supplies. Since ECL is less immune to noise some separation of supplies would be necessary. A final and very important consideration is that ECL logic is not considered state of the art LSI at this time. Therefore a TTL mechanization of the special purpose programmable controller is preferred. The selected digital scan converter functions, previously listed, which can be accomplished in this controller are listed in Table 40.

TABLE 40. SELECTED CONTROLLER FUNCTION

1. Selects input video and synchronizing signals.
2. Controls the integrator by supplying the appropriate integration constant, β, and the total number of range samples to be received, R_I.
3. Controls peak detector output clock and controls truncation logic by loading a new truncation map.
4. Controls memory input address generator by supplying start points and line slopes and incrementing the values as needed.
5. Interprets DAIS or other data interface.
6. Controls built-in-test functions.
7. Controls general purpose clock generator.
8. Controls display synchronizing generator by supplying a rate word.

4.5.3 Controller Description

The special purpose programmable controller consists of four main elements. These are the arithmetic and logic unit (ALU), the microprogram control and memory, the program operand memory and the controller I/O interface. Additional elements such as multiplexers, data selectors, and disconnects are also needed to route the flow of data. These elements are organized basically into a single address processor with microprogram control as shown in Figure 88.

The microprogram is stored in the control ROM as a sequence of control words. The output word of the control ROM is called the control word and it establishes the state of the various multiplexers, the ALU, and the registers. The control ROM itself is stepped more or less sequentially through its addresses by the program counter. A derived clock signal is used to step the program counter.

A 20 megahertz clock is received and divided by five to obtain a four megahertz clock and five intermediate phases. The four megahertz clock

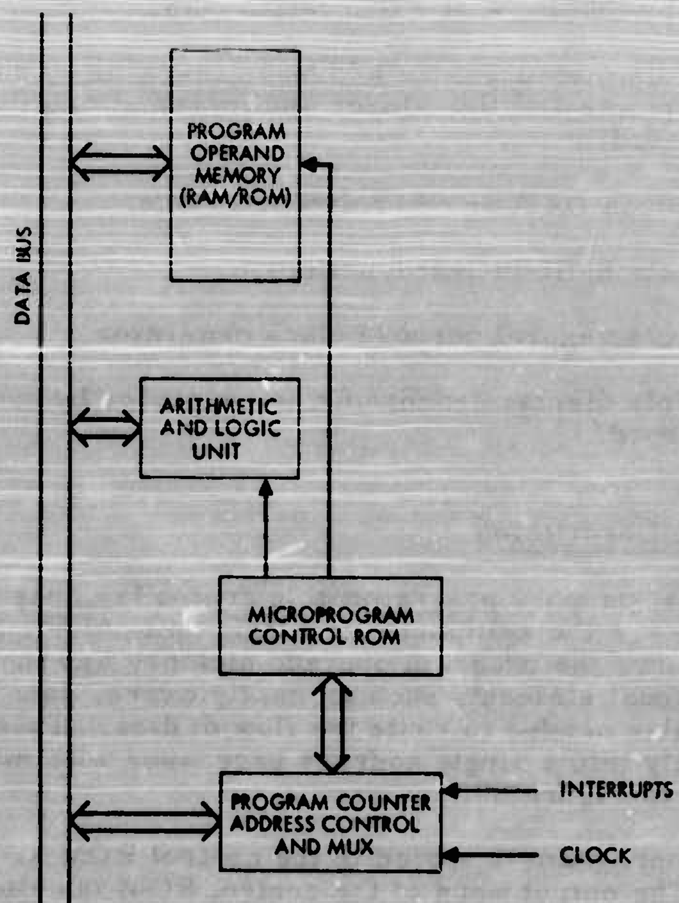


Figure 88. Special purpose programmable controller block diagram.

is used to step the program counter and cause new control words to appear. The five intermediate phases are used to ensure that data has settled before storing or gating data out. The phases are also used to execute multiple shifts within one program step and to speed up the multiplication routine. The multiple shift program steps are also very useful for selecting a part of a data word when an operation is required on only part of the data word or the data bits are not correctly aligned with the data bus or the receiving device. Without this multiple shift capability many program steps and memory locations would be wasted to accomplish the same function.

The four bit shift counter is used to control the multiple shift operations. It is loaded with the one's complement of the number of shifts desired for the data word in the ALU and the shifts are performed at the 20 MHz rate.

An arithmetic and logic unit is needed to increment numbers and perform computations to determine increments for sidelooking mode and symbol generation. The arithmetic and logic unit (ALU) is 16 bits wide and can add, subtract, complement, and increment input numbers. Included in the same package is a shift/storage matrix which can shift right, shift left, parallel load, or simply hold 16 bit data words. The mode of operation of the ALU is determined by certain bits of the control from the control ROM.

The working register store is used with the ALU to hold data temporarily during computation or to store results of computation. There are six latching registers, one shift register, and one address register.

The 512 x 16 constant ROM contains 256 values of sin θ from 0 to 90 degrees and 128 incremental corrections for sin θ, that are used in PPI mode. For a particular angle adding an incremental correction to the nearest stored value results in sin θ to an accuracy of fifteen bits. The remainder of the ROM is available for storage of video truncation breakpoints, line slopes, reciprocals, or any other constants needed.

The DSC Controller design is partitioned basically into the ROM memory section and the remaining elements. The ROM's would be contained on a separate module and changing from one aircraft system to another or updating an older system would involve replacing this single newly programmed ROM module.

This same design can be used as a microprogrammed processor for symbol generation control. The recommended controller design uses tri-state logic to simplify the bus connections. Converting this logic to LSI may involve more risk than is desirable. This is due to the fact that in tri-state design, gate outputs are connected directly together. Internal gate enable connections remove the drive currents from the output transistors (both pull-up and pull-down). If any of these output transistors are bad or fail, very large currents could flow in the chip. This would very likely cause sufficient damage to make the LSI wafer unsalvageable by pad relocation techniques. Hence, a much lower yield would be expected for tri-state LSI. For these reasons, the LSI design of the controller would probably be converted to straight TTL and ordinary multiplexers would replace the tri-state gates.

4.5.4 Programmed Controller Operation

The programming of the controller is best described by the monitor flow chart (Figure 89). The steps in the flow chart are carried out by the microprogram stored in the control ROM.

When power is switched on, the program counter is automatically cleared and the microprogram starts from location zero. From this start point the first microsubroutine attempts to read the new mode word from the DAIS interface (or other interface module for non-DAIS systems). This new mode word is stored and decoded as needed in the succeeding mode change subroutines. Within the mode change loop the controller sequentially:

Blanks the display screen to prevent distracting and incorrect data from being displayed.

Stores mode word data and any data which would be lost by succeeding subroutine operations. Thise could be for example the last value of θ used in an address calculation.

Selects the appropriate display synchronizing clock frequency.

Selects the appropriate video input line and A/D sample clock frequency.

Selects the feedback constant for the input integrator.

Selects the number of range bins to be stored. (These values are program stored as a function of mode.)

Generates a new video truncate map.

Performs the pilot confidence level module test if requested by pilot. This is an overall check of signal levels to the functional level.

If requested by maintenance, a detailed module test is performed possibly with the aid of an additional plug-in control program ROM and display readout test set. Defective modules could be easily identified and an exhaustive test reliably performed in a manner of seconds.

Unblanks the display to present data to the pilot.

When a new mode has been established and all the constants supplied to the rest of the DSC modules, the controller operates within the small address loop. Here the particular address equation for the existing mode is repeatedly solved to accomplish the actual scan conversion. Display line or radial slopes and starting points are sent to the input address generator at approximately the horizontal display line rate or the PRF rate.

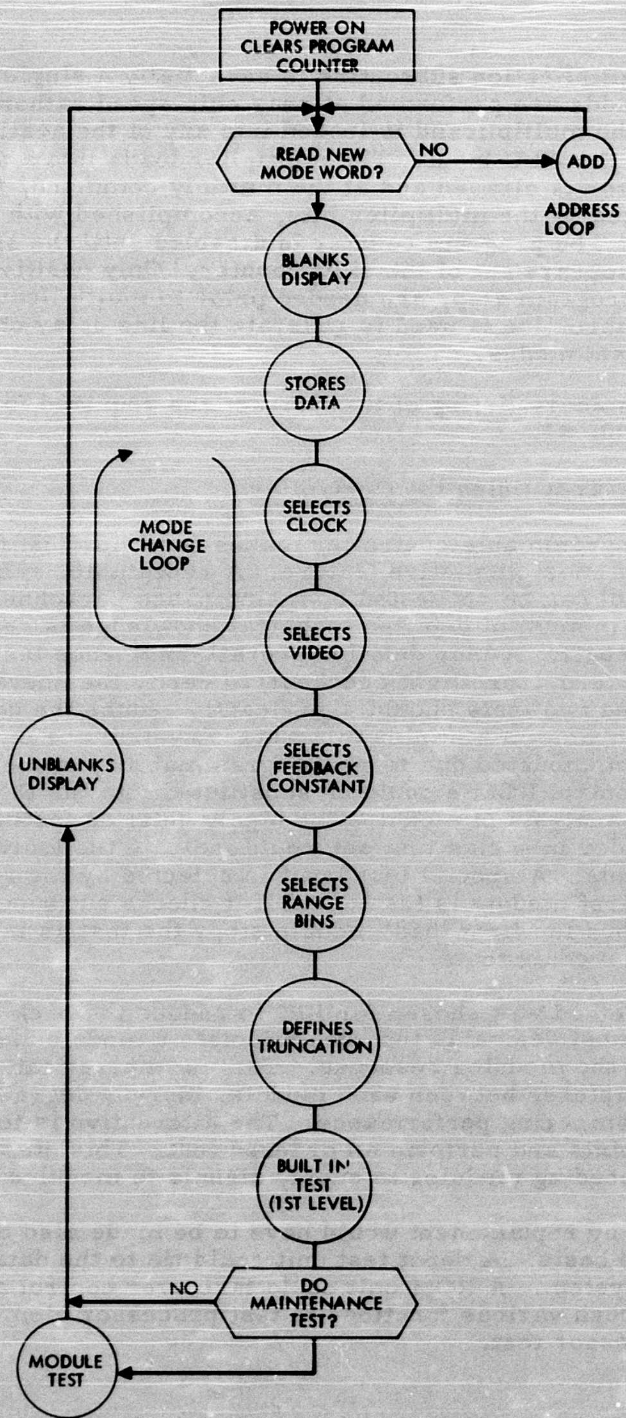


Figure 89. Monitor program.

The multiplication subroutine is essentially a single bit algorithm but the shifts and adds are performed at near chip speed rather than at program step speed. The multiplicand is loaded into any of the available data registers and is gated to the ALU input. The multiplier loads into a shift register. The ALU accumulator is cleared and at the multiply command, the accumulator loads as directed by the multiplier bits, accomplished with right shifts after each bit. The program counter is disabled until the shifts are completed and the carry appears out of the shift counter. Only positive numbers may be multiplied so program steps are needed prior to multiplication to correct signs. This subroutine is used to generate the line delay constant in the side-looking and offset modes.

A preliminary listing of the instructions required for this controller is shown in Table 41.

4.5.5 Built-in-Test Using the Controller

The programmable controller makes Built-in-Test (BIT) readily attainable and a most attractive feature. A repeatable, reliable test under program control can be requested by maintenance personnel to identify faulty modules. A minimum of detailed technical knowledge is required for module replacement repair. A less detailed overall confidence test is available on pilot command (e.g., preflight checkout) to verify the operational status of the DSC. These two tests should significantly reduce the cost of ownership by holding down time to a minimum. Future systems or unique installations are easily accommodated due to the programmability of the controller. Maintenance control ROM's could be substituted into the DSC to perform complete fault analysis of modules for highly detailed testing if needed. Readouts included in such a test set would indicate the individual testing steps and failure points. A special test input is selected by the receiver multiplexer. The first module is tested and if it checks out succeeding modules are tested. Thus the first 'bad' module stops the test as inputs are not valid for succeeding module tests.

This method was chosen for BIT to reduce the back panel wiring needed. The most desirable test would isolate a module and send inputs while watching the modules response. This is impractical. It would require a multiplexer between each module, thereby degrading reliability and possibly hampering performance. The alternative is to monitor all of the intermodule points and perform an ordered test. This step-at-a-time testing depends on preceding modules to supply signals to modules under test.

Repair by replacement would have to be made also on an ordered step-at-a-time basis. A depot test unit could tie to the data bus and monitor the complete system. A ROM unit could take over control and step the processor through various functions to test processor elements and do a complete processor test.

TABLE 41. PRELIMINARY INSTRUCTION LIST

Data Transfer
Load Accumulator - LA
Load Register - LQ, L1, L2, L3
Load Extended - LAE, LQE, L1E, L2E, L3E
Load Right Immediate - LARI, L1RI, L2RI, L3RI
Load Left Immediate - LALI, L1LI, L2LI, L3LI
Load Extended Immediate - LAEI, LQEI, L1EI, L2EI, L3EI
Load Double - LD
Load Double Extended - LDE
Load Multiple - LM, LMI
Load Multiple Extended - LME, LMIE
Load Selective - LSEL
Store Accumulator - STA
Store Register - STQ, ST1, ST2, ST3
Store Extended - STAE, STQE, ST1E, ST2E, ST3E
Store Double - STD
Store Double Extended - STDE
Store Multiple - STM, STMI
Store Multiple Extended - STME, STMIE
Store Selective - SSEL
Exchange A and Q Registers - XAQ
Assign - ASG
Arithmetic Instructions
Add - AA
Add Extended - AAE
Add Double - AD
Add Double Extended - ADE
Add Right Immediate - AARI, A1RI, A2RI, A3RI
Add Extended Immediate - AAEI, A1EI, A2EI, A3EI
Add Left Immediate - AALI
Substract - SA

(Table 41, continued)

Subtract Extended - SAE
Subtract Double - SD
Subtract Double Extended - SDE
Multiply - MA
Multiply Extended - MAE
Multiply Extended Immediate - MAEI
Divide - DA
Divide Extended - DAE
Divide Extended Immediate - DAEI
Logical Instructions
And - NA
And Extended - NAE
And Extended Immediate - NAEI
Or - OA
Or Extended - OAE
Or Extended Immediate - OAEI
Compare - CA
Compare Extended - CAE
Compare Right Immediate - CARI
Compare Left Immediate - CALI
Compare Extended Immediate - CAEI
Reset Bit - BIR
Reset Bit Extended - BIRE
Set Bit - BIS
Set Bit Extended - BISE
Test Bit - BIT
Test Bit Extended - BITE
One's Complement - OCA
One's Complement Double - OCD
Two's Complement - TCA
Two-s Complement Double - TCD

(Table 41, concluded)

Absolute Value - ABSA
Absolute Value Double - ABSD
Shift Instructions
Shift Left Logical - SLLA
Shift Left Logical Double - SLLD
Shift Left Cyclic - SLCA
Shift Left Cyclic Double - SLCD
Shift Rigth Logical - SRLA
Shift Right Logical Double - SRLD
Shift Right Arithmetic - SRAA
Shift Right Arithmetic Double - SRAD
Shift Right Cyclic - SRCA
Shift Right Cyclic Double - SRDC
Branch Instructions
Branch Indirect - BI
Branch Relative - BR
Branch Extended - BE
Branch and Link, Indirect - NAL1I, BAL2I, BAL3I
Branch and Link Extended - BAL1E, BAL2E, BAL3E
Branch Conditionally, Relative - BEQR, BNER, BLTR, BLER, BCTR, BGET
Branch Conditionally, Extended - BEQE, BNEE, BLTE, BLEE, BGTE, BGEE
Branch on Count, Relative - BCT1R, BCT2R, BCT3R
Branch on Count, Extended - BCT1E, BCT2E, BCT3E

4.6 Symbol Generator Design Study

The purpose of this section is to identify and define alternative approaches to the design of the in-raster display generator and to select and describe the approach best capable of meeting the design requirements described in Section 2.0. Design considerations germane to the display generation requirements are reviewed in order to isolate critical performance parameters that will narrow the choice of candidate design approaches. Trade-off analysis of hardware and software approaches are made to arrive at the recommended symbol generator design.

The approaches considered for in-raster symbol generation are restricted to all digital techniques. The selected approach, a programmable non-real time generator, requires a buffer memory and controller. The applicability of the controller described in Section 4.5 is discussed at the end of this tradeoff.

4.6.1 Tradeoff Criteria

A number of parameters and design features must be considered in order to compare and evaluate alternative symbol generating techniques. Included in these considerations are the following:

- Display data refresh
- Speed
- Display Capacity
- Display Data/Raster Synchronization
- Data Word Size
- Modularity
- Flexibility
- Reliability
- Size, weight, power consumption

4.6.2 Symbol Generator Trade-Off Analysis

To provide the MMSDS with the capability to display symbolic data in-raster entails the basic functions shown in the simplified block diagram, Figure 90. These functions include display data control of incoming data from various avionics subsystems, digital-to-video conversion of display defining parameters, and finally, raster synchronized transfer of video unblanking signals to the TV raster display.

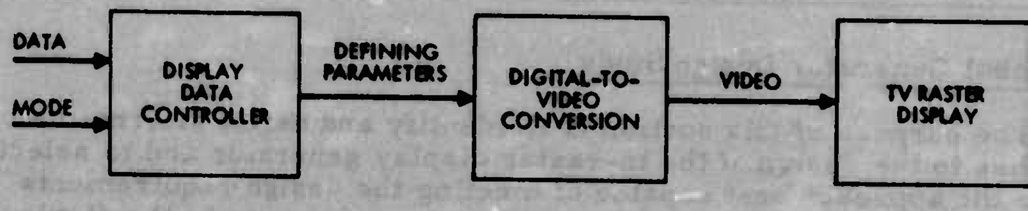


Figure 90. In-raster symbol generator/display system.

The display data controller function includes data buffering and sampling of input data, code conversion of input data words, coordinate conversion and formatting of real world input data into display coordinate data, storage of display field formats by display mode, ordering and listing of display defining data, and control of data transfers and processing of data.

The digital-to-video (D-V) conversion function operates upon display defining data (e.g., symbol type, size, position, intensity, etc.) and produces TV video unblanking signals. This D-V conversion process may be accomplished by digital hardware, computer software, or a combination of both. The D-V conversion process can be performed at real-time rates by generating unblanking video directly in synchronism with the TV raster. As an alternative, a digital video bit memory of the whole display data field (a refresh memory) may be utilized to allow non-real time, random sequence processing and loading of display data into video memory which is then read out at real-time raster rates. The symbol generation alternatives that may be analyzed include variations and combinations of real time or non-real time symbol generation mechanized by hardware and/or software techniques.

Real time hardware symbol generation is a possible symbol generation approach. However, software generation of symbol data, at real time rates, would require very high speed multiprocessors that may be marginal under high density and dynamic conditions. This approach has been excluded from the trade-off analysis. The non-real time hardware technique which employs a field refresh memory constitutes a very feasible approach to symbol generation for the MMSDS and is included in the trade analysis. A non-real time, programmable (firmware) approach using a field refresh memory is the third basic symbol generation approach that is included in the following trade off analysis. Firmware implies programs stored in ROMS.)

Real Time Hardware Symbol Generation

A real time hardware symbol generator approach suitable for the MMSDS shown in Figure 91. The symbol generator consists of a number of dedicated hardware modules, operating in parallel, at real-time raster rates to provide synchronized unblanking video for the TV indicator. In addition to the symbol generating modules, the symbol generator includes a display data controller, an interface data buffer, an address decode function, timing and control, and mode control. The display controller accepts serial data from the avionics interface, and performs data conversion and formatting operations to provide display defining parameter data for the various symbol generating modules. Display data words are fed to the modules as required to initialize the digital logic circuits of the symbol generating modules. Parallel word video data is mixed and serially shifted at TV line element rate to form bit video. Mode control establishes the avionics data required for display. Also, certain programmable functions such as presets, logic scaling,

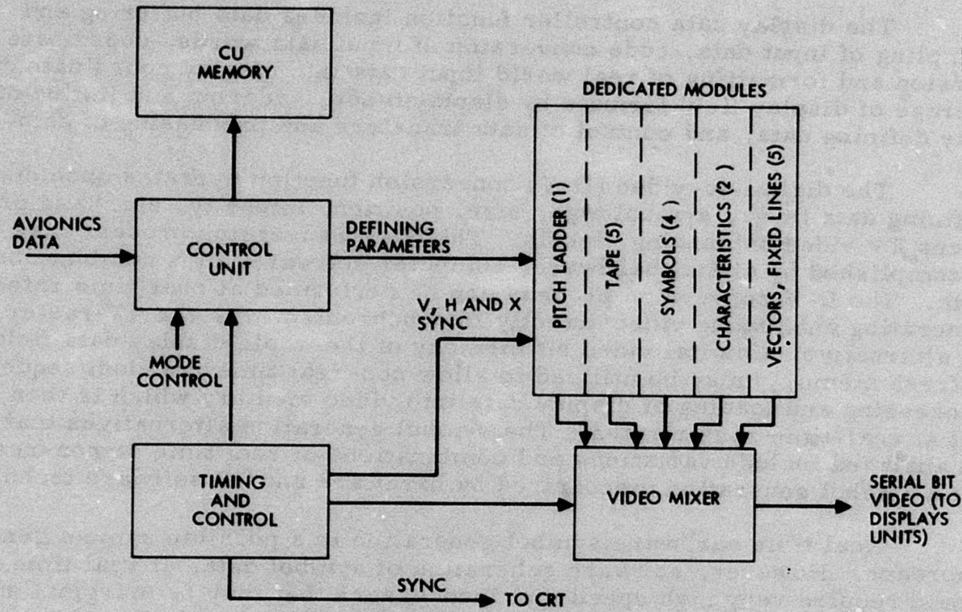


Figure 91. Real time, hardware symbol generator.

etc., are derived from mode control. Module functions are synchronized by field, line, and raster element synchronization signals received from timing and control.

The real time, hardware mechanized symbol generator is configured to be responsive to the general requirements implied by the symbol display in Figure 92. (Derived in Section 2.4.) The number of module types is determined by the different types of display data that are to be displayed. The number of modules required of any particular type is dependent upon the worse-case display mode requirement for the particular type of data to be generated for presentation. The types of display data (characters, symbols, lines, tapes, etc.) to be displayed is derived from Section 2.4 and the representative electronic display data graphics specified in MIL-STD-884B and MIL-D-81641(AS) specification.

The complexity of this approach is a function of the amount of symbology required. The baseline assumption is to provide the symbology in Figure 92. The IC count for real time, in raster symbol generator mechanization as shown in Table 42. The numbers shown in parenthesis indicate the number of functions included in the IC count. The hardware complexity estimate applies to the mechanization required to implement real time, in-raster symbol generation for an 875 line TV raster format. The IC count is higher if a 525 line or 1023 TV mode of operation is also included.

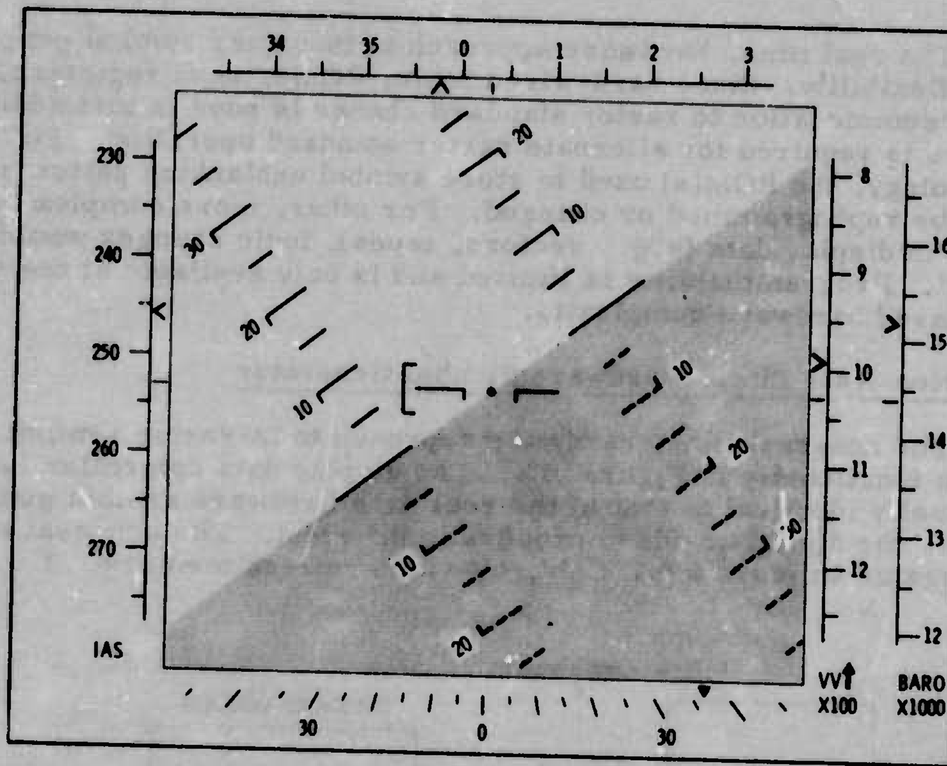


Figure 92. Symbology for advanced system application.

TABLE 42. IC COUNT - REAL TIME HARDWARE SYMBOL GENERATOR

Function	Number of IC's
I/O Controller	89
Mode Control	8
Timing and Control	10
Video Mix	9
Pitch Ladder Generator	62
Moving Tape Generator	200 (5 symbols)
Slewable H&V Line Generator	26 (2)
Discrete Symbol Generator	32 (2)
Diagonal Line Generator	24 (2)
Vector Line Generator	44
Total	504

The real time, hardware approach to in-raster symbol generation has limited flexibility. Since hard-wired logic, ROMs, shift registers, etc., are used, accommodation to raster standard change is poor in that additional hardware is required for alternate raster standard operation. For changes in symbology, the ROM(s) used to store symbol unblanking patterns would have to be reprogrammed or changed. For other, more complex types of changes in display data (e.g., vectors, tapes), logic changes would be required. Programmability is limited and is only available at the expense of increased hardware complexity.

<u>Non-Real Time, Hardware Symbol Generator</u>

The non-real time, hardware approach to in-raster symbol generation is shown functionally in Figure 93. The display data controller functions are virtually identical to that of the real time hardware symbol generator. However, the digital-to-video process is different. The non-real time symbol generator employs a full field, bit video refresh memory. The use of the

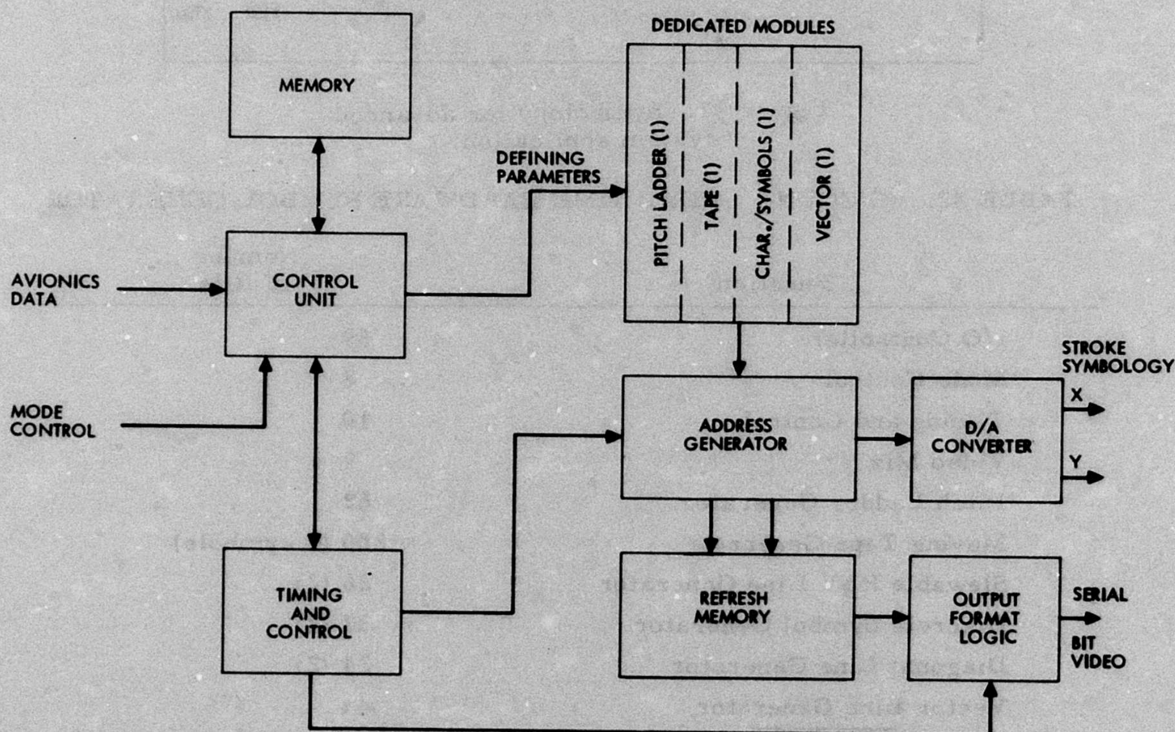


Figure 93. Non-real time, hardware symbol generator.

refresh memory allows random, serial operation of the dedicated hardware modules for initial display data field generation and updating. Only one dedicated symbol data generating module is required for each generic type of display data. Included are the pitch ladder generator module, the tape generator module, the discrete symbol/character generator module, and the vector generator module. The vector generator is used to generate the slewable horizontal and vertical lines as well as the fixed diagonal lines. The output of the dedicated modules in raster coordinates is converted into field memory coordinates by the address generator. Output format logic and timing and control is used to read out the field memory at raster scan rates.

Since address generation is required for loading unblanking video data into the field memory, a capability to provide stroke symbol output is also available. By means of D/A conversion, display field addresses can be converted into X and Y deflection signals for stroke symbol generation for non-raster displays such as Head-Up Display (HUD).

The flexibility of the non-real time hardware symbol generator is about as limited as the real time hardware symbol generator. The limitations are poor accommodation to raster standard changes, the need to change or reprogram ROMs for symbol changes, and to add or change logic for data format changes. However, increases in data density may be accommodated within the limits of available field memory write time. Programmability is generally as limited as the real time hardware approach.

The mechanization complexity in terms of an IC count is estimated as shown in Table 43. The same display format shown in Figure 92 is assumed. The number of ICs required for symbol generation modules is much lower than is the case for the real-time hardware mechanization because only a total of four modules are required. If a conic data generation requirement is added to overall symbol data generation requirements, then an additional conic display data generation module would be required. Offsetting this reduction in dedicated hardware modules is the substantial number of IC's required to mechanize the field refresh memory. Overall the IC count is lower for the non-real time hardware approach than for the real-time approach.

Programmable Symbol Generator

The programmable symbol generator (shown in Figure 94) is similar in operation to the display data controller of the hardware approaches. Input avionics data is conditioned, decoded as required, and formatted into display defining parameter data for the display generator. Display defining parameter data are structured into display bit form for rapid transfer to the display generator during refresh memory loading periods. A dot/line-segment chaining technique is used to attain high coding efficiency, minimize controller memory size, and maintain a dot/line segment transfer rate of 1.5 MHz.

TABLE 43. IC COUNT – NON-REAL TIME HARDWARE SYMBOL GENERATOR

Function	Number of IC's
I/O Controller	89
Mode Control	8
Timing and Control	10
Pitch Ladder Generator	62
Moving Tape Generator	40
Vector Line Generator	44
Discrete Symbol Generator	32
Input Format Logic	40
Field Refresh Memory	48
Output Format Logic	18
Total	391

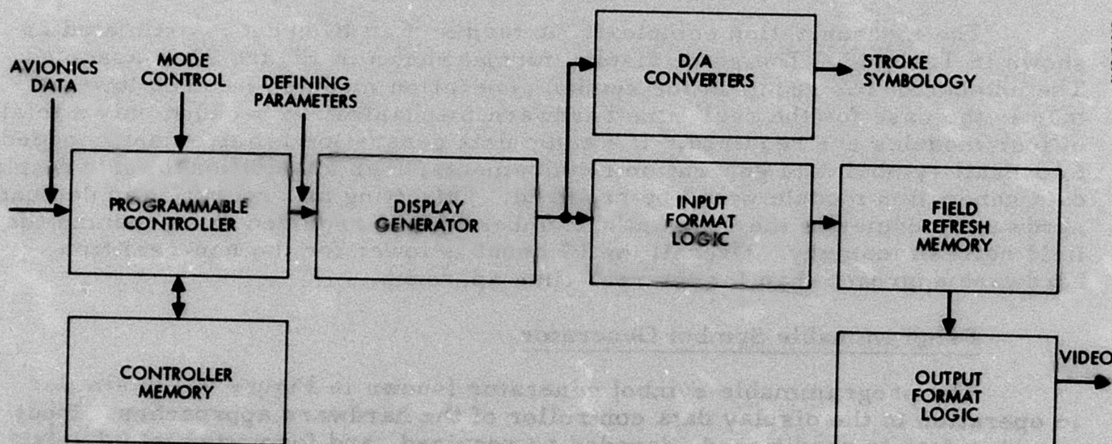


Figure 94. Programmable in-raster symbol generator.

The display generator operates upon display parameter defining data that is in the form of direction codes of a predefined length. Display data output of the display generator in raster coordinates is formatted into memory address data for loading into the field refresh memory. Output format logic under timing and control of the programmable controller is used to read out the refresh memory at real time raster rates. D/A conversion of the output of the display generator may be used to generate stroke symbology.

Due to the inherent flexibility of firmware, changes in symbol data and raster standards are easily accommodated. Changes in symbol library, symbol font detail, or symbol size require only changes in micro programs. A change in raster standard, from 875 lines to 525 lines, can be easily accommodated by rescaling the length of the line segments used to develop symbols. It is evident, then, that firmward flexibility also provides excellent growth capability of the symbol generator. Within the constraints of display list memory capabity and available refresh memory write time, the symbol generator can accommodate symbol library additions, alternate display field formats, and new generic classes of display data such as conics.

The mechanization complexity of the programmable symbol generator in terms of an IC count is estimated as shown in Table 44. It is seen that this IC count is lower than either hardware approach to symbol generation while offering the inherent advantages of superior flexibility. It should be noted that the IC count for this approach is not affected by the quantity of symbology. The complexity of the other two approahces varies with the number and type of symbology. Therefore as the number of symbols ultimately employed increases the programmable symbol generator becomes even more attractive.

TABLE 44. IC COUNT – PROGRAMMABLE SYMBOL GENERATOR

Function	Number of IC's
Programmable Controller	89
Symbol List Decoder	75
Symbol Chain Generator	62
Input Format Logic	40
Refresh Memory	48
Output Format Logic	18
Total	332

Trade Off Summary

A summary of the symbol generator trade off analysis is presented in Table 45. As is evident from the table, the software programmable approach has distinct advantage over the alternate hardware approaches. Its main advantage is its programmability, flexibility, and accommodation to growth, change, and increased capabilities.

As a result of the trade off analysis of in-raster symbol generator techniques, the programmable symbol generator is recommended for fulfilling symbol generator requirements of the MMSDS. The programmable symbol generator mechanization is described in more detail in Volume II, Section 2.

TABLE 45. IN-RASTER SYMBOL GENERATOR TRADEOFF SUMMARY

Parameter	Programmable	Real Time Hardware	Non-Real Time Hardware
Display Data Refresh	Display Data Updated as Required	Generates Data at Refresh Rate	Display Data Updated as Required (≪ Refresh Rate)
Speed	3M Bits/sec	34.8M Bits/sec	3M Bits/sec
Display Capacity	Limited by Size of Buffer Memory	Limited by Processing Speed	Limited by Size of Buffer Memory
Display Data/Raster Sync	Critical	Very Critical	Critical
Modular	Yes	Yes	Yes
Programmable	Yes	Limited	Limited
Flexibility	High	Hardware Limited	Hardware Limited
Buffer Memory Required	Yes	No	Yes
Symbol Font	Any	Limited by ROMS	Limited by ROMS
TV Raster Compatibility	Symbol Size Controlled by Firmware for Different Raster Standards	Additional Symbol ROMS Required for Different Raster Standards	Symbol
Stroke Symbol Capability	Yes	No	Yes
Mechanization Complexity	1.0	1.5	1.3
Growth Potential	High	Hardware Limited	Hardware and Time Limited
Reliability	Highest (Greater than 10,000 hrs. in LSI Configuration)	High (All Digital)	High (All Digital)

4.6.3 Symbol Generator Controller

The controller described in Section 4.5 can also be used to provide the symbol generator control function. However, the symbol generator controller requires more memory than the DSC controller. Storage is required for an executive program, a display generating program, two temporary storage display lists, and a set of utility routines. The total storage required is about 8K by 16 bits. Of this, 4K by 16 must be RAM and the other 4K would be ROM. Two thousand words of the RAM are needed to store the new display list as it is being built up by the display generating program. The other 2K by 16 contains the previous frame display list and is read out to the symbol chain generator while the new display list is being generated. Readout alternates at about a 20 Hz rate between the two 2K by 16 RAMS. Figure 95 illustrates the memory required.

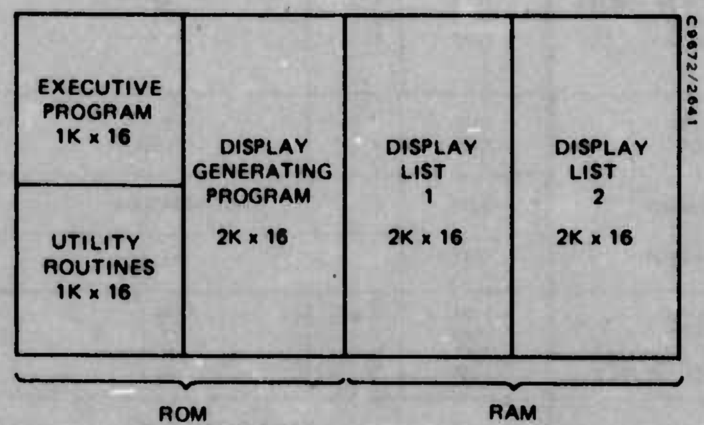


Figure 95. Symbol generator controller memory requirements.

The program generates an entirely new display at about a 20 Hertz rate. Thus for a display frame rate of 60 Hz, the readout display list would be successively read three times while a new symbol list is being generated and stored. That is, the actual update time for a symbol on the display is 50 ms.

Figure 96 lists the utility routines which are called by the display generating program to build a display list. These routines require 1K by 16 bits of ROM.

Studies and laboratory evaluations have indicated that in raster symbol quality is significantly improved with multiple gray shade encoding. The brute force technique for providing this capability, would substantially increase the symbol refresh memory in Figure 94. Special coding techniques may provide the desired improvement without resorting to excessive memory size increases. It is, however, beyond the scope of this study to pursue the design of such techniques.

DATA WORD						
		0 1 2 3	4	5	6 7 8 9 10 11 12 13 14 15	
VIDEO SETUP	INDICATOR	0000	0	-	- - - - - - . NO. 1 2 3 4	
	INTENSITY *	0000	1	-	COLOR / SATURATION / BRT	
POSITION SETUP	Hoo	0001	0	-	Hoo	
	Voo	0001	1	-	Voo	
	Ho	0010	0	-	Ho	
	Vo	0010	1	-	Vo	
	Ho AND RESET	0011	0	-	Ho	
	Vo AND RESET	0011	1	-	Vo	
	ADD Ho	0100	0	-	Ho.	
	ADD Vo	0100	1	-	Vo	
CHAIN SETUP	SIN	0101	0	-	SIN θ	
	COS	0101	1	-	COS θ	
	VIDEO *	0110	VIDEO PATTERN			RELATIVE MODE VIDEO
	LENGTH	0111	L-1			
CHAIN	LINE	1000	0	-	N-1	N = LENGTH OF LINE
	DOT	1000	1	-	N-1 = 3	N = TIME ON SPOT
	CHAIN ABS	1001	0	-	N-1	N = NO. OF SEGMENTS
	CHAIN REL *	1001	1	-	N-1	N-1>0, N = NO. OF 2 BIT BYTES
		CHAIN DATA ⟶				
	NO-OP	1010				
		1010				
		1010				
		1010				
		1010				
INTERFACE	NO. WORDS	1011	NO. WORDS TO BE LOADED			
	LOAD INTO	1100	LOAD INTO			
	BR	1101	BRANCH			
	MPB	1110	MARK PLACE, BRANCH			
	RETURN	1111	0	-	- - - - - - - - - -	
	EOD	1111	1	-	- - - - - - - - - -	

C4599/1491

Figure 96. Utility routines

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